1972

A petrographic study of the stratigraphy of Australian coal seams

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A PETROGRAPHIC STUDY OF THE STRATIGRAPHY OF AUSTRALIAN COAL SEAMS

by

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A thesis submitted to the University of New South Wales for the degree of Master of Science, 1972

Statement of Originality.

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

ACKNOWLEDGEMENTS

I wish to thank:

Mr I.E. Newnham, Director, Minerals Research Laboratories, C.S.I.R.O., for permission to work on this project at the Division of Mineralogy;

Drs A.C. Cook and G.H. Taylor, my supervisors, for continued advice in relation to the research work and the compilation of this thesis;

the staff of the Drawing Office of the Division of Mineral Chemistry, in particular Mrs Vera Barhatov, Mrs Anna Kuperman and Mr John Catlin;

Mr E.G. Shrubb of the Division of Mineral Chemistry for photographing and reproducing all the diagrams at the appropriate size;

Drs M.Y. Smith and A. McKenzie for providing valuable assistance in writing the computer programs used in this work;

the editors of the Journal of the Geological Society of Australia, the Australasian Institute of Mining and Metallurgy, the Queensland Government Mining Journal and Dr P.A. Hacquebard for permission to reproduce diagrams and tables in the Appendix and Section 10 of this thesis;

Miss Helen Terrey for her diligence in typing this manuscript.

The petrographic analyses used in this work were made by a number of analysts over a period of approximately twenty years. The analysts include the present author, Dr G.H. Taylor, Dr S.St.J. Warne, Mr J.A. Nielsen and Dr A.C. Cook.

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1. SUMMARY

Petrographic analyses of over one hundred Australian coal seams of Permian and Triassic age are used to determine within seam and between seam variations and the conditions prevailing during seam formation. Tests on groups of coals show that a change in coal type is dependent on the type of coal immediately preceding (Markovian properties). From this dependence most probable sequences of coal variations can be derived.

For individual seams major changes in coal type are represented by characteristic plies, from which standard profiles of each seam are derived. Type seam sequences are derived from the standard profiles for each coal measure group, when more than half of the profiles are similar. Marked similarities exist between the type seam sequences.

The distribution of the types of petrographic profiles of all seams is found unlikely to be due to chance. The sequences found from the Markovian properties, the type seam sequences and the distribution of profiles are few and similar.

All these results indicate that the seams are deposited under ordered conditions and that the major control is an internal one, most probably a response of plant growth and decay to the changing conditions associated with the increase of peat thickness.

Comparison with Carboniferous coals from England and Canada shows that similar petrographic profiles are developed in them.

2. INTRODUCTION

Rhythm in sedimentary sequences may involve features ranging in magnitude from annual varve couples to the rhythm related to major orogenies. Between these extremes many kinds of supposedly rhythmic sequences have been reported. Coal-bearing rhythmic sequences, or cyclothems (Wanless and Weller, 1932), are particularly well known from the Carboniferous. Well-developed rhythmic cyclothemic sequences may include several tens of repetitions, and nearly all are composed very largely of essentially deltaic deposits, or shallow water marine/deltaic deposits.

Booker (1960) considers that during the Permian there were two major rhythms recorded in two alternations of marine and fresh water sedimentation in the Sydney Basin. Superimposed on the major rhythms are numerous smaller rhythmic alternations. The major cycles are thought by Booker to be due to tectonism, the minor rhythms to eustatic changes in water level. The Greta, Tomago and Newcastle Coal Measures may represent periods of glacial recession. The minor cycles of the Sydney Basin Permian differ from those of the Pennsylvanian of the United States in that they tend to be wholly freshwater, whereas the Pennsylvanian rhythms contain characteristic alternations of thin marine and freshwater units.

Duff (1967) noted the differences between Sydney Basin cycles and the classic North American and European cyclothems, but assumed that significant cycles exist and made statistical analysis of the assemblages of interseam strata. He also concluded that the cyclic sedimentation was deltaic and alluvial in the Southern Coalfield, but of an undecided environment in the Northern Coalfield.

The coals of cyclothems have been investigated extensively and it has been found (Smith, 1962) that there is a similar sequence of petrographic types in different seams. Smith recognized this sequence from the study of the vertical succession of spores in British Carboniferous coal seams and the petrological types associated with them. Four distinct spore and lithological associations have been described, as well as the types of environment which each is most likely to represent.

If such sequences exist in Carboniferous coals, they may well be found in Australian Permian and Triassic coals also. However, many Australian coals are very low in exinite, some containing virtually no spores at all, so that any attempt to establish the general existence of a vertical succession in Australian coal seams would have to be made using petrographic data alone. Any work done on spore assemblages would however be of great value for interpreting the environment of deposition of the coals. Fortunately Smith (1962) has correlated spore assemblages with petrographic types, so that petrology alone can be of some use in environmental reconstruction, provided always that the rock types in Australian coals can be equated with those distinguished by Smith.

Most of the economic seams of Australia have been sampled in subsections by the C.S.I.R.O. Division of Mineralogy as part of a continuous survey of Australian coal resources. The bulk of these seams have been from the Permian coal measures of New South Wales and Queensland, and the Triassic coal measures of Queensland.

As part of the survey program, the chemical and physical properties, including petrographic composition, of all the coals sampled have been determined. Petrographic analyses of one or more samplings of over one hundred seams have been made (many of them by the present author), providing information on both the variations in coal type within any particular seam and the petrological variations and similarities amongst different seams. These data form the basis of the present study.

For the purposes of analyses, the seams sampled have been divided into subsections, which were then individually analysed. Very often the petrographic composition of these subsections varies markedly from one to the next, so that each would appear to be representative of a different depositional environment.

For various reasons the original subsection selection could not be regulated solely to suit this study. However, accepting these unavoidable limitations on the quality of the data, the subsection sequences have been tested for non-random characteristics using a first order Markov model. Sequences were tested using data for all the coal seams separately, as a single set and also in a hierarchy of sub-sets.

Using a different approach, when a seam had been divided in such a way that adjacent subsections had a very similar microlithotype content, these subsections were combined into "characteristic plies", so that these plies, then, are the representatives of the varying environments. A petrographic profile of each sampling of each seam was built up from the characteristic plies, which comprise the initial subsections, or combinations of these.

When a seam has been sampled more than once, the petrographic profiles of the individual samplings very often show a similar pattern of variation in the microlithotype contents of their plies. In such cases the corresponding plies from each profile have been correlated, as rock unit equivalents (not necessarily time-rock unit equivalents) and a "standard" profile of the seam has been compiled from the average thicknesses of the characteristic plies and their average microlithotype contents. In this way standard profiles for approximately one hundred seams of the Permian and Triassic of New South Wales and Queensland were obtained, derived from approximately two hundred and fifty samplings.

The standard profiles of seams of the same coal measures and from the same coalfield were compared, and there is, in many cases, a similar sequence of variations in the petrographic contents of their plies. When the profiles of half or more of these related seams show this similarity, a "type seam sequence" has been compiled from the standard profiles, in a way analagous to the compilation of the standard profiles from the individual seam samplings. A type seam sequence was established for all but one of the coalfields studied.

Even these type seam sequences show similarities to one another, and it appears that nearly all the seam profiles could have their major features expressed in terms of a relatively small number of basic patterns (idealized patterns).

To this point the division of the seams into the original subsections, the delineation of characteristic plies, the formation of standard profiles and of type seam sequences has all been carried out on more or less subjective bases. However, again accepting the limitations on the quality of the data, statistical tests were applied to the types of sequences found. It appeared from the generation of the type seam sequences that the majority of the coal seams studied had followed a limited number of patterns of development, which in turn implied that some ubiquitous and repeated factor, or factors, was controlling the deposition of the peat in the swamps. The distribution of the sequence types was tested for randomness, using a Chi Squared test. The naturally occurring configurations of coal seam profiles were compared with the theoretically possible variations which could be found in seams with from two to six plies.

The ecological conditions prevailing during seam formation have been considered at the ~~general~~ generalized level of the type seam sequences and comparisons drawn between these Australian coals and coals from other world-wide localities.

3. PREVIOUS WORK

One of the early workers in the field of the use of coal petrology in coal seam stratigraphy is Hacquebard, who in 1943 described an extensive study of different seams from all over the South Limburg (Holland) coalfield, "for the purpose of examining the correlation of coal seams with the aid of petrographic profiles".

His idea was that coal petrography may be used for correlation if the composition of the coal is similar in a horizontal direction but with pronounced differences vertically. This composition depends on the vegetation which comprises the original peat and the conditions under which it formed. These conditions repeatedly change, but the vertical order of succession of various components may remain constant for some distance. Although there is some evidence to the contrary for Australian coals, he thought it unlikely that the vertical and horizontal variations of one seam would be identical with those of another.

Hacquebard (1943, 1951, 1952) found it possible to divide a seam into several intervals in which certain banded ingredients predominate, or show a specific succession or alternation; these were called petrographic divisions. From these he found that the petrographic divisions represent varieties of coal which originated under specific circumstances during peat formation. The bright coals were derived from the woody constituents, probably originating in the more forested parts of the peat bog. The dull coals originated in areas that bordered open water.

In summary, Hacquebard found the vertical succession of the petrographic divisions of a seam to be different from that of seams above and below; and that the horizontal changes of the divisions are not very great within about a three mile limit. Studies of the Harbour seam in the Sydney coalfield, Nova Scotia, even showed certain characteristic horizons to have much the same petrographic composition over the entire coalfield.

The present study on Australian coals indicates that characteristic horizons are widespread, in agreement with Hacquebard; but that seams from several coal measures do have the same vertical succession of petrographic divisions as seams above and below, as for example coals from the Greta, Tomago, Baralaba and Collinsville Coal Measures.

In another paper by Hacquebard, Birmingham and Donaldson (1967) the results of a comparative study between the petrography of six coal seams and the depositional aspects of their respective coal basins are discussed. "The type of basin controls the nature of the peat and ultimately the character of the coal. ...In this study coal type has been related to coal facies, which is an expression of swamp environment."

Coals formed in paralic and limnic basins are discussed. In paralic basins the water level in the marsh is largely controlled by eustatic variations in sea level, which have an undulating character. Some diagnostic features of paralic basins are (1) marine sediments within the coal measures; (2) great lateral extent and uniform thickness of seams; (3) petrographic variations in the seam profile and (4) termination of seams by splitting and digitation.

Limnic basins represent true lacustrine basins and their coal measures are characterised by both coarse and very fine fluvic-lacustrine sediments. The coal seams are often very thick and of limited extent, rapidly changing in thickness and quality laterally.

This interpretation of environmental changes in peat swamps from petrographic variations within coals has been developed even more extensively by Hacquebard and Donaldson (1969).

Falini (1965) has pointed out that the position of the water level is closely related to the shape of the basin. This position in turn controls to a very large extent the type of vegetation, the mode of peat preservation and ultimately the type of coal.

Perhaps the work most relevant to the present study is that of Smith (1962), who carried out a petrological and palynological investigation of a number of coal seams in the Yorkshire Coalfield. He found four distinct assemblages of miospores, each assemblage being more or less associated with coal of a distinctive petrographic type, and that their vertical sequence is similar in the different seams. The simplest sequence is Lycospore - Transition - Densospore - Transition - Lycospore phases. The Lycospore phase is most often associated with high vitrite plus clarite coals, the Densospore phase with the more duritic coal and the Transition phase with coals intermediate between the very bright and dull coal. The Incursion phase may interrupt the sequence at any stage, and samples of the Incursion phase occur in coals containing clarodurite, durite and fusite. The possibility that at least part of the sequence, and particularly the crassidurain, was the result of climatic factors, and not simply environmental factors such as degree of drainage, or depth of water covering the peat surface at the time of deposition, is suggested.

Changing environmental conditions brought about changes in vegetation composition, which is reflected in the variations in the frequency and vertical distribution of spores in coal seams. The spore assemblages examined by Smith show that different horizons in a seam have different dominant species and that there is a regular pattern in the sequences of changes.

"The existence of a petrographic and palynological sequence implies a progressive change in the environment which affected both the vegetation and the mode of its decomposition." Seams in areas as far apart as South Wales, Yorkshire and Durham, deposited more or less contemporaneously, possess similar spore assemblages which may differ significantly from those of other seams above and below, indicating that some common environmental factor must have been operating. suggested (Smith) that fluctuating water levels are a major factor in determining the occurrence of the Incursion phase, but they are not the primary cause of the sequence of phases, beginning with the Lycospore and ending with the Densospore phase, and that the influence of climate on peat formation in Carboniferous times should be considered.

Peat will form wherever the water level is at, or just above, the surface of the ground for long periods irrespective of climate. Once begun, if the climate is wet and the atmosphere very humid, the peat will accumulate above the original ground surface. The development of the raised bogs of temperate climates is known to be the result of a succession of vegetation cycles. Although the rate of peat formation depends on the climate, "the changes in the vegetation and the peat type are largely due to the control of the edaphic conditions by the plants themselves". (Smith, 1962).

The sequence of phases found by Smith is either due to a peat structure analagous to the raised bogs, with a succession of vegetation types, or to climatic changes during deposition. Both factors may even have operated.

Smith concludes that the peat formation was initiated under a shallow covering of stagnant water, the vegetation being forest and the miospore assemblages belonging to those of the Lycospore phase.

The water cover was gradually withdrawn, either due to eustatic changes in sea-level or by raising of the bog surface through peat accumulation in a humid climate. This produced more aerobic decomposition, and changes in edaphic conditions, brought about by one or other or both of these factors, occurred. The forest was replaced by more open vegetation, richer in species, the miospore assemblages belonging to those of the Transition phase.

Coals assigned to the Densospore phase may be attributable to climatic factors such as high precipitation and humidity, and possibly change in temperature and edaphic factors, for instance absence of surface water and high acidity. Decomposition was initially aerobic and proceeded further than in any other environment.

A return to earlier climatic conditions may give rise to Transition phase vegetation again, in association with massive micrinite (tenuidurain). The increase in vitrinite following a Densospore phase is most easily explained by the presence of groundwater cover brought about by subsidence.

The above succession was often interrupted by flooding, which brought in varying amounts of mineral matter and semifusinite, and had a catastrophic effect on the existing vegetation. The miospore assemblage of this phase (the Incursion phase) is particularly rich in species, and has a distinct petrography. It is almost always followed by a reversion to the Lycospore phase.

Bell (1966) concluded that "seam profiles showing the disposition of marker horizons within a seam are of more value in the recognition of a coal than are the maceral and microlithotype analysis figures for the seam as a whole". A seam studied in detail, the Beaumont seam, had a profile typical of many Carboniferous coals, bright at the base, dull at the top, and from this Bell deduced that a widespread and uniform factor such as regional changes in the level of the water table had affected the development of the seam. The dull coal accumulated under a higher level of water than that which existed during the accumulation of the bright coal sequence.

He suggested that tenuidurains represent periods of inundation due to local flooding, which is in agreement with Smith's idea on tenuidurains, but crassidurains indicate a widespread increase in the water table level. This last is in direct opposition to the origin proposed by Smith for crassidurains: he considered them to have formed in a possible absence of surface water.

Spackman, Riegel and Dolsen (1969) have made a study of the geological and biological interactions in the swamp-marsh complex of Southern Florida. Peat and peaty deposits have been developing in the area for four thousand years, interacting with the marine sedimentary processes near the coastline. Three environments have been described along the coastal fringe, one an example of intertonguing of peat and clastic sediments, where a wedge of peat is underlain by marine marl and overlain by lime-mud and shell fragments. A second is a tidal flat environment covered with a mixed sediment of peat and lime-mud, with the development, by erosion of the flats and lowering of the land level of a different vegetation from the original. The third coastal type is one of islands of organic sediments, on which forest flourishes, cut by river channels.

However, the three coastal environments bear little resemblance to the inland fresh-water marsh and swamp environments. The marsh-land consists of a "sea" of saw-grass and spike rush with scattered "islands" of trees. The spike rush grows in water slightly deeper than the saw-grass, producing a freshwater marl or lime-mud sediment, the origin of which is related to algal mats which abound in this environment. The saw-grass derived sediment is typically very black, granular or amorphous peat. Eventually the saw-grass invades the spike rush environment, burying the lime-mud and demonstrating the ability of plant succession to produce thedevelopment of a new type of sedimentation at a given site without the aid of geological activity. However, other sedimentary processes may reverse the sense of environmental changes at any time. Such geological and biological phenomena must operate in the formation of several different peat types, and are not solely related to lime-mud and saw-grass peat accumulation.

Peat types of the forested sites are usually coarser in texture, contain more lignin, and are distinctly different from the sediments of the marsh environment. In some areas invasion of open-water by cypress trees occurs, where the depth of the water in shallow depressions is too great to permit colonization of the site by either saw-grass or spike rush. Eventually such an area is gradually covered with cypress. Peat accumulates from cypress debris and hard-woods begin to occupy the site even before the peat reaches the water surface. As the peat surface rises the tree island is eventually occupied solely by hardwoods. This also shows that plant successions can cause the superposition of one peat type upon another without the intervention of geological phenomena. The environments described for the Southern Florida marsh complex are not static. They move vertically in response to subsidence and peat development and horizontally in response to marine transgression and regression.

From statistical analysis of borehole sections through the Illawarra and Newcastle Coal Measures of the Sydney Basin, Duff (1967) noted the difference between the Sydney Basin cycles and the classic North American and European cyclothems, but assumed that significant cycles exist. He suggested that in the Southern Coalfield cyclicity is due to sedimentational processes inherent in the deltaic and alluvial conditions envisaged during Permian times. In the Newcastle Coalfield however, lack of sedimentological details makes it impossible to name any one mechanism of cycle formation.

Because of the absence of seat-earths for some of the coals associated with these cycles, Duff puts forward the idea that their origin may have been similar to that of peat found to-day in the Malayan swamps, where a forest vegetation grows on peat which is floating on water. "Growth of peat from decaying vegetation takes place with the base of the peat sinking downwards owing to the weight of waterlogged material above." In this case the vegetation would have little effect on the sediments below. A possible objection to this proposal is that the Malayan swamps exist in a tropical climite, whereas the Permian climate in Australian is thought by some authors to have been much colder. Cook and Read (1968) suggested that such rafts ought to give rise to characteristic structures within seams but concluded that none was evident in the coals examined by them.

Despite the lack of seat-earths, proof of vegetation growth in peat areas does exist in the form of vertical tree stumps and possible glossopterid roots beneath several seams. Glossopterids were probably deciduous and Duff proposes that the annual debris of leaves and other material might have been carried by water to accumulate with mud, perhaps forming the carbonaceous shale found beneath most seams, and eventually shrubs, then trees would establish themselves. However, the majority of Australian coals commence with bright coal, generally thought to be the remains of a forest vegetation.

Work on Australian coal seams using petrographic profiles has been done by Branagan (1962) and Davis (1968, 1969). Branagan introduced the idea of a "standard section" for the Borehole seam, Newcastle Coal Measures, in which various persistent plies and bands have been named by the miners. Davis (1968, 1969) used petrographic profiles to effect correlation for Permian coal seams in Queensland.

Cook and Read (1968) found a marked similarity between a coal seam from the Clyde River Coal Measures, New South Wales, and the Greta Coal Measures. They believe the depositional facies of the coals were similar, except that the Clyde River seam formed in a small closed basin, whereas the Greta Coal Measures were deposited over an extensive area. As the coal type was found not to depend on basin size an autochthonous origin for the coals is more likely than an allochthonous one. The absence of large plant fragments is probably due to an absence of large tree-like vegetation and an abundance of smaller forms. As climate controls both the type of flora and the peat forming conditions, which in turn influence the petrographic features, they suggested that the similarities between the Clyde River and Greta Coal Measure coals are ~~is~~ due to a similar climate.

Haan (1967) has developed two coal type classification schemes, one for field, the other for laboratory logging, during a detailed study of the Main Lower seam (Blackwater Group, Queensland). He has used them to correlate units within the seam. The scheme for laboratory logging showed that the petrographic types occurred in definite cycles, and this cyclic character enabled extremely accurate intra-seam correlation. The seam is considered to be "in situ", with lateral changes in coal type due mainly to differential subsidence, and vertical changes to climatic variations. Dull coals are believed to have formed during dry periods, bright coals during wet periods.

The petrographic type cycles were attributed to changes in ground water level with respect to the peat surface, reflecting long term climatic rhythms. However, Haan has subsequently modified his conclusions as to the cause of the changes in petrographic types as a result of his continuing work on this topic (personal communication).

Most of the work using petrographic profiles for coal seam stratigraphy has concerned European and North American coals. Hacquebard (1943, 1951, 1952) and Bell (1966) are of the opinion that the groundwater level is an important controlling factor in coal seam formation, whilst Smith (1962) considers climate and possibly the plants themselves, to have been of primary importance. Possible origins for Australian coal seams include floating islands of peat, with the base sinking down due to the weight of waterlogged material above (Duff, 1967), and the proposals of Cook and Read (1968) who consider climate to be a major factor controlling the nature of the peat.

4. APPLICATION OF FIRST ORDER MARKOV CHAINS TO COAL SEAM SEQUENCES

(a) Introduction

Over a number of years more than one hundred coal seams from the coalfields of Australia of Permian, Triassic, Jurassic and Cretaceous ages have been sampled by the C.S.I.R.O. Division of Mineralogy. Many of the more economically important seams have been sampled several times, providing information on intra seam variations as well as information on the differences or similarities amongst different seams.

All pillar, channel and bore core samples of seams are divided initially into subsections on the bases of their macroscopic appearance and an X-ray shadow examination. Criteria for subdivision are, for example, the relative brightness of the coal, the fineness of its banding and the proportion of mineral matter within the coal. At the Division of Mineralogy, a four inch (approximately ten centimetres) lower limit is usually placed on coal subsection thickness to ensure that enough material is available for all the chemical and physical tests to be carried out. An upper limit of three feet (approximately ninety centimetres) is also usually maintained to ensure that all detail of a seam is not lost by too coarse sectioning. In this way quite slight changes in the type of coal comprising a seam are recorded.

Included in the many tests carried out on the coal are petrographic analyses. For petrographic analyses the coal is crushed to

-1/16" (BS mesh 10), mounted in cold setting resin (astic), and the polished surface of the grain mount is examined in reflected light under oil immersion. Microlithotype analyses are carried out in compliance with the definitions of the International Committee for Coal Petrology (1963). Microlithotype analyses were chosen to work with because they have been carried out in the Division for some twenty years, thus providing a large store of petrographic information in this form. The analyses have been done by several geologists, but the consistency of results has been maintained by frequent comparative tests within the laboratory. Maceral analyses, although made, have not been nearly so extensive.

Examination of all these microlithotype data has suggested that the variations in petrographic content within a seam are not random but occur in a sequential or ordered manner. This implies that preceding events have some influence on succeeding events.

To determine objectively whether the changes in coal type occur in a non-random succession, a mathematical model has been set up and tested.

(b) <u>Choice of a statistical test for coal type variations within a seam</u>

Krumbein (1967), on the choice of statistical models for geological processes, suggests that where there is a pattern in the rock succession, as in cyclic sedimentation, the changes of state should be examined "in terms of their relative probabilities of occurrence".

The "underlying pattern of rock succession" present in cyclic sequences is a description which could be applied to the changes of coal type found in the Australian seams, and so a probabalistic model would seem an appropriate choice, to test the randomness of the coal type variations.

When transitions between successive bedding units are dependent on immediately previous events, a "memory" effect is present, and the process is commonly referred to as a Markov process. The probability of deposition of a coal bed, for example, may depend on whether an underclay was deposited during the previous event. In the simplest case a model has a one step memory and is referred to as a first-order Markov process (Harbaugh and Merriam, 1968).

A Markov chain is a sequence of discrete states in time or space in which the probability of the transition from one state to a given state in the next step in the chain depends on the previous state. "The general form of a Markov chain is such that it contains a finite number of states, and the probabilities associated with the transitions between states are stationary with time." (Harbaugh and Bonham-Carter, 1970).

The coal seams under study have

(i) a suspected underlying pattern in their coal type variations;

(ii) the data on them can be expressed in the form of discrete states;

(iii) there are a finite number of states.

However, the transitions between states may not necessarily be stationary with time. Any attempt to remove the time trend would be largely subsective, and in the opinion of the author would have no advantage over the methods used in the following sections, five and six. Also the effect of variations with time would be to obscure sequences, rather than enhance them.

Apart from the possibility of the transitions being non-stationary with time, these are the properties which are needed to set up a Markov chain model; this model would show whether the probabilities associated with the transitions from one state to another are dependent on the previous state.

(c) Testing for the Markov property

"The transitions in any series of observations that involve either discrete-state or discrete-time phenomena can be described by a matrix of transition probabilities provided...that there is a finite number of states in the system." (Harbaugh and Bonham-Carter, 1970).

These transitions may be purely random, or may even show preferences which could arise purely due to chance. Therefore the transitions found in the coal seams must be tested to find whether they are random or non-random, and if non-random, whether this is likely to be due to chance or not.

Procedure

The test for the Markov properties of the subsections of a seam was carried out on the vitrite plus clarite content. For each seam the subsections are assigned to one of four states, α, β, γ, and δ, by dividing the difference between the maximum and minimum vitrite plus clarite values found in all the subsections of a given seam section by four, and then comparing the vitrite plus clarite contents of the individual subsections with the four divisions (see Table 4.1). α is the state with the lowest vitrite plus clarite content, δ is the state with the highest. A fifth category, ε, is designated for dirt bands which occur in the seams. The data have been tested including and excluding dirt bands, because in many sequences the number of dirt bands is so large that they obscure relations between the other states.

As a transition from one state to the same state is of no interest for the study of progressive changes of coal composition, where adjacent states are the same they are considered together, that is, an embedded chain is used (Krumbein and Dacey, 1969). A further reason for using an embedded chain is that this structuring of the data is more consistent with the methods used in choosing the original subsections.

Starting at the base of the seam, the transitions from one state to another are recorded across the rows of a five by five matrix: (four by four matrix when dirt bands are excluded), with a zero diagonal, as α to α, β to β, etc. transitions have been eliminated. This is the <u>Tally Matrix</u> (see Table 4.1). Summing across the rows gives the number of transitions for each state; summing down the columns gives the number of occurrences of each state to which another state may pass.

Having recorded the observed transitions in the tally matrix, the transitions expected based on the proportions of each state present are recorded in an <u>Independent Trial Matrix</u>. The expected transitions are calculated from the number of actual occurrences of each state (summing in columns). For example, a subsection in the α state would be expected to pass into any other of the four states in proportion to the number of times that each one occurs. The percentage of transitions from α to the β state is calculated from

$$\frac{\beta}{\beta + \gamma + \delta + \varepsilon} \times \frac{100}{1}, \text{ etc.}$$

To bring the observed and expected transitions into the same form, a <u>Transition Probability Matrix</u> is derived from the tally matrix, by expressing each transition of a row as a percentage of the total transitions in that row.

To test whether the observed transitions are the same or not as the expected ones, the independent trial matrix is subtracted from the transition probability matrix, to give a <u>Difference Matrix</u>. The highest value in each row of the difference matrix is the transition most disparate from a chance occurrence. If the observed and expected transitions were the same, the values in the difference matrix would be zero, and the observed transitions would be taken to be independent of one another.

Approximately three hundred and fifty samplings of seams of Permian, Triassic, Jurassic and Cretaceous ages from New South Wales, Queensland and South Australia have been analysed in the above manner (computer programs MARKOV for five states, author Dr Martin Smith; for four states, MINKOV, author Dr Alan MacKenzie, Fig. 4.1), and their difference matrices calculated. None ~~were~~ was found to contain all zero values, or, in other words, transition preferences were shown by all seams. However, preferences may arise purely due to chance, and the probability of this being the case with these particular transitions must be found before they can be defined as definitely possessing Markov properties.

For any individual seam sampling, the number of transitions is so small as to be statistically non-significant. Meaningful results can only be obtained by considering groups of samplings of one or a number of seams together, so that the number of transitions involved becomes significant.

The coals were therefore put into the stratigraphically defined groups:- Greta Coal Measures, Tomago Coal Measures, Newcastle Coal Measures (excluding the Moon Island Beach Sub-Group), Newcastle Coal Measures (Moon Island Beach Sub-Group), Illawarra Coal Measures, Lithgow Coal Measures, Collinsville Coal Measures, Baralaba Coal Measures (Baralaba, Moura, Nipan, Theodore and Blackwater districts all taken separately), Ipswich Coal Measures (Tivoli and Blackstone Formations), Walloon Coal Measures and Leigh Creek Coal Measures: sixteen groups in all. (See Appendix for a description of these units.)

The sequences of the transitions having the highest marginal probabilities to occur for each state, obtained from these sets are shown in Tables 4.2 and 4.3, in numerical order. Each sequence is expressed as five digits, each digit position representing the coordinate of the column for α, β, γ, δ, and ε transitions respectively. For example, 21433 means

Initial state

$\alpha \rightarrow \beta$ (2)

$\beta \rightarrow \alpha$ (1)

$\gamma \rightarrow \delta$ (4)

$\delta \rightarrow \gamma$ (3)

$\varepsilon \rightarrow \gamma$ (3)

State with highest marginal probability in difference matrix

Where values in the one row of the difference matrix are equal, both probabilities are recorded. Thus any group of coals may have one or more probable sequences.

These difference matrices were tested by the Chi Square method to determine whether the distribution of values is likely to be due to chance.

The square of each element of the difference matrix was divided by the corresponding elements of the independent trial matrix,

$$\left(\frac{(\text{observed} - \text{expected})^2}{\text{expected}}\right),$$

and these numbers summed for each matrix. The results of the Chi Square Tests are shown in Tables 4.2 and 4.3. In almost all cases the probabilities of the transition being purely random are less than one in one hundred, so that in general the sequence of coal plies may be considered to possess Markov properties.

When dirt bands are considered as part of the coal seam sequence, several different groups show the same sequences, and only one of them, the Greta Coal Measures, has a sequence which could be due to chance alone. When the dirt bands are excluded from the succession, fewer groups have the same sequence, and five of them could be due purely to chance: the Greta Coal Measures (both sequences), the Blackstone Formation, the Newcastle Coal Measures (Moon Island Beach) and the Illawarra Coal Measures.

It would appear then, that dirt bands (as a category of rock) do play a significant part in the ordered deposition of coal seams.

As the stratigraphy of the coal seams is to be considered on a general level only, these sixteen sets were further grouped on the basis of stratigraphic relationship. For example, all the coals of the Baralaba Coal Measures from the districts Baralaba, Moura, Nipan, Theodore and Blackwater, were grouped together. The sequences derived from these groups, and for all coals combined are shown in Tables 4.4 and 4.5, as well as their values of Chi Squared and the derived probabilities.

Having shown that the majority of coal seams have Markov properties, it remains to consider what type of coal is dependent for its deposition on what other type of coal, and the form of the sequences derived from this dependence.

The <u>Baralaba Coal Measure</u> sequences are 51234 with included dirt bands, and 2143 with dirt bands excluded. These may be written:

$$\begin{tikzcd} \varepsilon \arrow[r] & \delta \arrow[r] & \gamma \arrow[r] & \beta \arrow[r] & \alpha \arrow[llll, bend right, dashed] \end{tikzcd}$$

and

$$\delta \rightleftarrows \gamma \qquad \beta \rightleftarrows \alpha$$ respectively.

The five state sequence is a cyclic chain, and may be represented as in Fig. 4.2. It is a sequence of progressive upward decrease in vitrite plus clarite content of coal in equal steps, the vitrite plus clarite-poor coal at the end of the cycle being followed by a dirt band, which is the beginning of the next cycle.

The four state sequence as is, consists of two oscillating closed sets. As it is desired to know how the four states are related if possible, the second most probable transitions given by the difference matrix must be considered, where necessary, to provide links between the four states. When this is done, the sequence found is 4123, which may be written

$$\delta \rightleftarrows \gamma \longrightarrow \beta \rightleftarrows \alpha$$

which is again a sequence with vitrite plus clarite content decreasing upwards in equal steps (Fig. 4.3) with the coal lowest in vitrite plus clarite followed by coal highest in vitrite plus clarite. So first preferences show an oscillation between two states, which would give a profile of alternating vitrite plus clarite-rich, vitrite plus clarite-poor plies, with a second preference tendency for an upward decrease in vitrite plus clarite content.

The sequences for the <u>Illawarra, Lithgow and Newcastle (Moon Island Beach) Coal Measures</u> are 54524 and 4441, which may be written:

$$\varepsilon \rightarrow \delta \rightleftarrows \beta \qquad \gamma \rightarrow \varepsilon \rightarrow \delta \rightleftarrows \beta \qquad \alpha \rightarrow \varepsilon \rightarrow \delta \rightleftarrows \beta$$

and

$$\delta \rightleftarrows \alpha \qquad \beta \rightarrow \delta \qquad \gamma \rightarrow \delta$$ respectively.

In the five state sequence a closed set is reached from any starting point due to the preference for transitions to dirt bands and then the oscillation between δ and β states from this. Even when second preferences are taken, no cyclic sequences can be found from these coals.

Taking second preferences from the four state matrix, the sequence is 2341, which can be written

$$\begin{tikzcd} \delta \arrow[r, shift left] & \alpha \arrow[l, shift left] \arrow[r, dashed] & \beta \arrow[r, dashed] \arrow[ll, bend left] & \gamma \arrow[lll, bend right] \end{tikzcd}$$

This is cyclic, and is shown graphically in Fig. 4.4. The primary form is oscillating, which would give a profile of alternating vitrite plus clarite-rich, vitrite plus clarite-poor plies, with a secondary tendency for vitrite plus clarite to increase upwards.

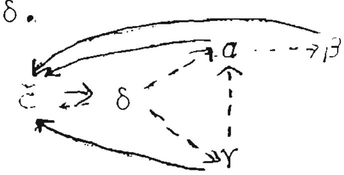
The <u>Ipswich Coal Measure</u> sequences are 55554 and 2123, which may be written

$$\varepsilon \rightleftarrows \delta \qquad \alpha \dashrightarrow \varepsilon \qquad \beta \dashrightarrow \varepsilon \qquad \gamma \dashrightarrow \varepsilon$$

and

$$\delta \rightarrow \gamma \rightarrow \beta \rightleftarrows \alpha$$ respectively.

The five state sequence is one in which the $\varepsilon \rightarrow \delta$ transition becomes absorbing. Second preferences give a choice between the γ and α states from δ.



A cyclic sequence is established if the transitions are followed through in the order $\begin{tikzcd} \varepsilon \arrow[r] & \delta \arrow[r] & \gamma \arrow[r] & \alpha \arrow[r] & \beta \arrow[llll, dashed, bend right] \end{tikzcd}$. This is illustrated in Fig. 4.5.

In the four state sequence a closed set is reached once either the α or β states are entered. Taking second preferences, a sequence 3421 is found:-

$$\begin{tikzcd} \delta \arrow[r, dashed] \arrow[rr, bend right] & \alpha \arrow[r, dashed] \arrow[rr, bend left, leftrightarrow] & \gamma \arrow[r, dashed] & \beta \arrow[lll, dashed, bend right] \end{tikzcd}$$

This is a cyclic sequence with a profile of alternating vitrite plus clarite-rich, vitrite plus clarite-poor plies (Fig. 4.6).

For <u>all coals</u> combined the sequences are 51554 or 51154 and 2143. These may be expressed as

$\varepsilon \rightleftarrows \delta \quad \alpha \rightarrow \varepsilon \quad \beta \rightarrow \alpha \rightarrow \varepsilon \quad \gamma \rightarrow \varepsilon \qquad \varepsilon \rightleftarrows \delta \quad \alpha \rightarrow \varepsilon \quad \begin{matrix} \beta \rightarrow \alpha \rightarrow \varepsilon \\ \gamma \rightarrow \alpha \rightarrow \varepsilon \end{matrix}$

and

$\delta \rightleftarrows \gamma \qquad \alpha \rightleftarrows \beta$ respectively.

In the five state sequences, all states lead to the $\varepsilon \rightleftarrows \delta$ absorbing oscillation. Even second preferences do not give rise to a cyclic sequence.

The four state sequence consists of two closed sets. When second preferences are taken, the sequence 4123 is found, which is the same as that for the Baralaba Coal Measures (Fig. 4.3).

Consideration of coal seam sequences in these large groups has led to the establishment of four basic types of succession: (a) progression upward to low vitrite plus clarite coal (Figs. 4.2 and 4.3); (b) progression upward to high vitrite plus clarite coal (Fig. 4.4); (c) progression upward to low vitrite plus clarite coal with a following high vitrite plus clarite ply (Fig. 4.5) and an alternation of high and low vitrite plus clarite coal plies (Fig. 4.6).

These patterns of coal variations are, theoretically, the ones most likely to occur in the majority of the petrographic profiles of the seams. For confirmation of this, the coals must now be examined as individual seams, to see what occurs at this level.

TABLE 4.1.

Bayswater Seam Bore S1

Tally Matrix

	α	β	γ	δ	ε	
α	-	1	0	0	8	9
β	0	-	1	0	3	4
γ	2	0	-	0	0	2
δ	0	0	0	-	1	1
ε	7	3	1	1	-	12
	9	4	2	1	12	

$$\frac{V_{max} - V_{min}}{4} = \frac{58 - 0}{4} = 14\tfrac{1}{2}$$

α	state	0 - 14	9
β	"	15 - 29	4
γ	"	30 - 44	2
δ	"	45 - 58	1
ε	"	dirt bands (DB)	12

Sub-sections	Vitrite plus Clarite	State
A	DB	ε
B	58	δ
C	58	δ
D	DB	ε
E	9	α
F	DB	ε
G	16	β
H	DB	ε
J	11	α
K	13	α
L	DB	ε
M	22	β
N	DB	ε
O	DB	ε
P	1	α
Q	tr	α
R	tr	α
S	1	α
T	DB	ε
U	1	α
V	DB	ε
W	1	α
X	DB	ε
Y	12	α
Z	DB	ε
AA	11	α
BB	DB	ε
CC	13	α
DD	34	γ
EE	24	β
FF	DB	ε
GG	23	β
HH	13	α
JJ	14	α
KK	41	γ
LL	42	γ
MM	DB	ε

TABLE 4.1. (cont.)

Independent Trial Matrix

	α	β	γ	δ	ε
α	–	20	14	4	62
β	38	–	8	4	50
γ	35	15	–	4	46
δ	33	15	7	–	45
ε	56	25	13	6	–

β	4
γ	2
δ	1
ε	12
	19

α	9
γ	2
δ	1
ε	12
	24

α	9
β	4
δ	1
ε	12
	26

α	9
β	4
γ	2
ε	12
	27

α	9
β	4
γ	2
δ	1
	16

Transition Probability Matrix

	α	β	γ	δ	ε
α	–	12	0	0	88
β	0	–	25	0	75
γ	100	0	–	0	0
δ	0	0	0	–	100
ε	59	25	8	8	–

Difference Matrix (TPM – ITM)

	α	β	γ	δ	ε
α	–	–8	–14	–4	+26
β	–38	–	+17	–4	+25
γ	+65	–15	–	–4	–46
δ	–33	–15	–7	–	+55
ε	+3	0	+5	+2	–

$\alpha \rightarrow \varepsilon$
$\beta \rightarrow \varepsilon$
$\gamma \rightarrow \alpha$
$\delta \rightarrow \varepsilon$
55153 $\varepsilon \rightarrow \gamma$

TABLE 4.2.

Sequences found for groups of seams, dirt bands included

Groups of seams	Sequence	χ^2	p
Leigh Creek	21433	75.70	< 0.01
Nipan	(51134	181.67	< 0.01
Blackwater	(51134	224.04	< 0.01
Callide	(51154	194.02	< 0.01
Baralaba	(51154	189.83	< 0.01
Collinsville	51214	120.47	< 0.01
Moura	(51234	152.99	< 0.01
Blackwater	(51234	224.04	< 0.01
Baralaba	51254	189.83	< 0.01
Theodore	51424	217.65	< 0.01
Greta	(53154	26.07	> 0.10*
Baralaba	(53154	189.83	< 0.01
Baralaba	53254	189.83	< 0.01
Illawarra	54514	48.12	< 0.01
Walloon	54552	175.98	< 0.01
Walloon	54553	175.98	< 0.01
Newcastle (MIB excl.)	55154	172.30	< 0.01
Newcastle (MIB)	55514	39.47	< 0.01
Lithgow	55521	229.55	< 0.01
Tivoli	(55554	114.29	< 0.01
Blackstone	(55554	81.16	< 0.01
Tomago	(55554	95.63	< 0.01

TABLE 4.3.

Sequences found for groups of seams, dirt bands excluded

Groups of seams	Sequence	χ^2	p
Callide	2112	193.01	<0.01
Tivoli	2121	25.89	<0.01
Tivoli	2141	25.89	<0.01
Callide	2142	193.01	<0.01
Blackwater	(2143	35.45	<0.01
Leigh Creek	(2143	37.07	<0.01
Baralaba	2313	30.72	<0.01
Walloon	2421	113.54	<0.01
Blackstone	2423	24.22	>0.01*
Theodore	3142	85.99	<0.01
Greta	3411	3.03	>0.99 *
Greta	3413	3.03	>0.99 *
Newcastle (MIB excl.)	4112	38.56	<0.01
Collinsville	4121	24.49	<0.01
Moura	4123	159.58	<0.01
Theodore	4142	85.99	<0.01
Tomago	4143	42.27	<0.01
Lithgow	4311	57.96	<0.01
Nipan	4413	104.82	<0.01
Newcastle (MIB)	(4441	11.79	>0.30 *
Illawarra	(4441	15.14	>0.10*

* Sequence does not depart significantly from random

TABLE 4.4.

Sequences with dirt bands included

Supergroups of seams	Sequence	χ^2	p
Baralaba Coal Measures (Baralaba, Moura, Nipan, Theodore and Blackwater districts)	51234	117.63	<0.01
Illawarra, Lithgow and Newcastle (Moon Island Beach) Coal Measures	54524	42.22	<0.01
Ipswich Coal Measures (Tivoli and Blackstone Formations)	55554	92.58	<0.01
All coals combined	51554	31.39	<0.03

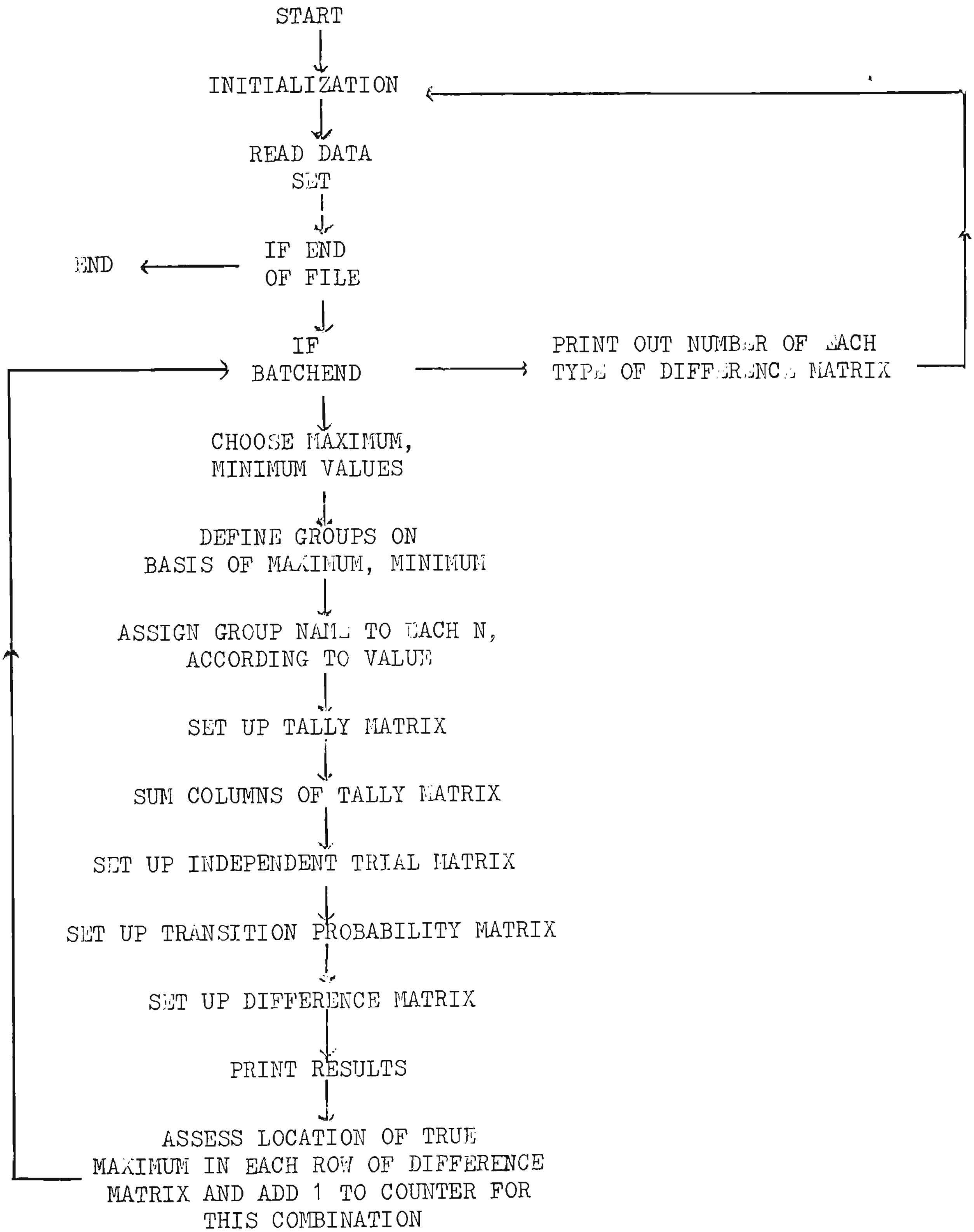
TABLE 4.5.

Sequences with dirt bands excluded

Supergroups of seams	Sequence	χ^2	p
Baralaba Coal Measures (Baralaba, Moura, Nipan, Theodore and Blackwater districts)	2143	24.99	<0.01
Illawarra, Lithgow and Newcastle (Moon Island Beach) Coal Measures	4441	9.88	>0.50
Ipswich Coal Measures (Tivoli and Blackstone Formations)	2123	17.40	>0.05
All coals combined	2143	6.71	>0.80

FIGURE 4.1.

Flow sheet of computer program



Baralaba Coal Measures
(Five States)

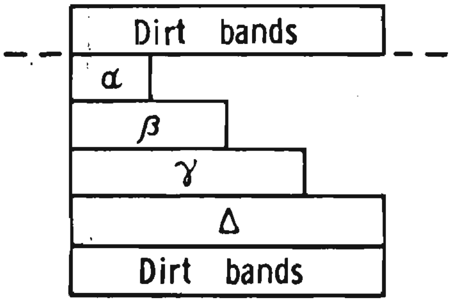


Fig. 4·2

Baralaba Coal Measures
(Four States)

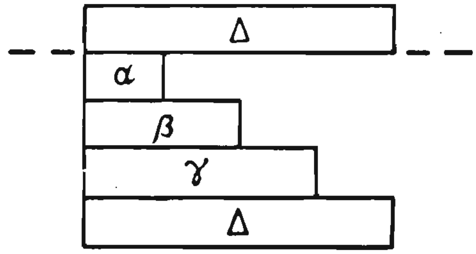


Fig. 4·3 (cf 4·2)

Illawarra, Lithgow, Newcastle (Moon Island Beach Sub-Group)
Coal Measures (Four States)

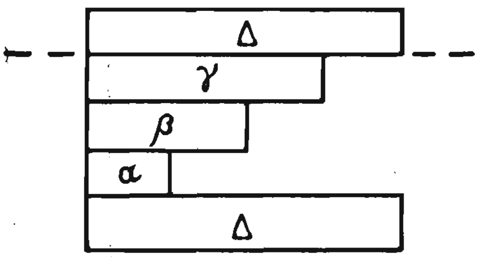


Fig. 4·4

Ipswich Coal Measures
(Five States)

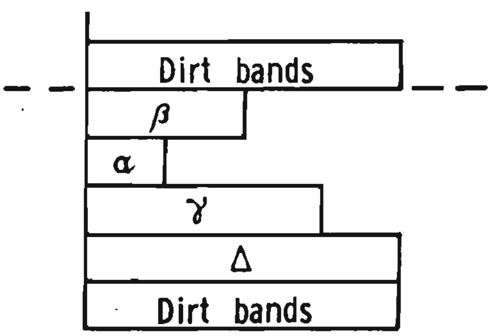


Fig. 4·5

Ipswich Coal Measures
(Four States)

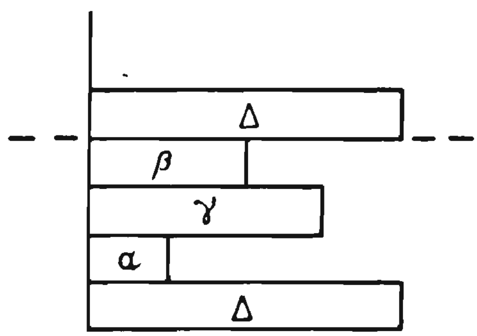


Fig. 4·6

Graphic representations of the sequences derived for the sets of coals listed in tables 4·3 and 4·4

5. THE DELINEATION OF CHARACTERISTIC PLIES AND FORMATION OF STANDARD PETROGRAPHIC PROFILES

(a) Introduction

In the preceding section it was found that coals when considered at certain group levels (for statistical significance) showed dependency of transitions from one state to another. To test for this dependency it is necessary to use only one of the microlithotypes found in the coals.

As the number of transitions for any seam is in the main too small to be statistically significant, it is also useful to consider the transitions in the individual seams making subjective decisions on what constitutes a significant state in the seam. Taking into account all the four main microlithotype groups (vitrite plus clarite, intermediates, durite and fusite) may also make the results more significant in terms of depositional environment than if only one of the groups is used. Therefore changes in state in the following four sections for each seam are based on a consideration of the simultaneous variations in the major microlithotype constituents.

(b) Characteristic plies

The microlithotype contents of the subsections in a seam are depicted very clearly by the use of histograms. The thicknesses of the subsections are drawn to scale, and the percentages of the microlithotypes vitrite plus clarite, intermediates (duroclarite, clarodurite, vitrinertite and inertivitrite), durite, fusite, shaly coal and minerals are drawn as separate histograms. Thus variations in petrographic contents are readily discernable (Fig. 5.1.).

Seam profiles have been drawn up in this manner for approximately one hundred seams from the Permian and Triassic coal measures of New South Wales and Queensland, listed in Table 5.1.

Although the division of the seams into subsections shows the variations in their petrographic contents, often a seam is so finely divided that in any one sampling small scale features which appear in no other sampling of the seam are picked out. Such features are of local interest, but when the seam history as a whole is to be considered, larger scale variations of wide extent must be looked for. For example, on examination of a petrographic profile such as that of the Arties seam from the Tomago Coal Measures of New South Wales (Fig. 5.1), it was noticed that there were several quite marked changes in the petrographic composition of the seam from base to top. From the base of the seam upwards, subsection R has a high vitrite plus clarite content (approximately 80%), with low intermediates, no durite (as there is so little durite throughout the seam, there seems little point in further mention of it), and little fusite. Subsection Q presents a marked change in petrographic type with less than 40% vitrite plus clarite and a large increase in intermediates, which change persists into subsection O. Subsection R is taken to represent one set of depositional conditions, and subsections Q and O to represent a quite different environment. With subsection M conditions changed again, with an increase in the vitrite plus clarite and drop in intermediates content, with little variation through subsections K, G, E and D. The final change back to an environment producing lower vitrite plus clarite and higher intermediates contents is represented in Subsection B.

Thus four separate sets of depositional conditions have been recognized in the Arties seam, and on the assumption (with initially only one sampling of the seam) that these conditions were widespread and are thus characteristic of the seam in general, the profile is divided into four "Characteristic plies" - the first being subsection R, the second subsections Q and O; the third subsections M, K, G, E and D and the fourth, subsection B. As dirt bands have frequently been found to be discontinuous from one sampling area to another, they have not been considered in the delineation of the characteristic coal plies. Similarly the shaly coal and mineral matter is not considered to be a good diagnostic feature for deciding on changes in the coal forming environment, unless it has been recorded as syngenetic, diagenetic or epigenetic.

The microlithotype contents of the characteristic plies were found from the weighted averages of the contributing subsections. The Arties seam, as divided into its characteristic plies is shown in Fig. 5.2. The plies depict the large scale changes in the seam, i.e. ones likely to be widespread and common to most, if not all, samplings of the seam, which tend to be masked by the small scale, or local, variations represented by the subsections.

In general, a change in absolute percentages of at least 20%

in two or more of the microlithotype constituents from one subsection to another was sought before separation into a new ply was made. The thickness of coal over which the change occurs is of secondary importance to the lateral persistence or otherwise of the change. However, in some seams, such as the lower seams from the Newcastle Coal Measures of New South Wales, there may not be a change of 20% in any microlithotype from the bottom to the top of the seam, and so relative changes in the microlithotype percentages must be considered. The Victoria Tunnel seam, for example, has a high vitrite plus clarite content, and low intermediates, durite and fusite contents throughout. Nevertheless, when the total inertinite content of subsections is considered, as represented by the intermediates, durite and fusite contents combined, significant variations between subsections can be found. As well as the changes in total inertinite, there is a general trend of an upward decrease in vitrite content, so when these two factors are considered in conjunction, the Victoria Tunnel seam, and others similar to it, can be divided into characteristic plies (Fig. 5.3). In such vitrite rich seams, relatively slight increases in inertinite are considered to represent notable changes in the depositional environment.

Thus, although for most seams characteristic plies are readily recognizable because of marked changes in the petrology of the seam, there are seams where ply delineation is highly subjective.

Characteristic plies are intended to represent widespread conditions of deposition which prevailed for an appreciable length of time; i.e. a phase in the accumulation of the peat when more or less similar conditions prevailed over a large, if not the total, area of the peat forming environment probably for some thousands of years. Within the area over which a ply is developed the type of coal (and its thickness) may vary laterally to some extent, but it should be possible to identify any ply in a seam section by considering it with the plies around it, i.e. by considering the sequence of changes which occurred in the seam, not just the localized conditions which prevailed at one point. A bright coal ply may include several dull bands, possibly more of them in one locality than another, but the overall general conditions would be those which produced bright coal.

Most seams studied have been divided into from three to five characteristic plies, so that each ply on average represents about a quarter of the total deposition time.

The characteristic ply is a very broad subdivision, which can encompass facies changes and sporadic lenses of both coal and inorganic sediments. The main uses of the plies are as a guide to the major features of the depositional history of a seam and for the construction of a "standard" profile of the seam.

(c) Formation of standard petrographic profiles

The standard petrographic profile of a seam is the profile of the seam compiled from the maximum number of characteristic plies, in stratigraphic order, which have been delineated for that seam.

If only one sample of a seam is available, the standard profile of that seam is the petrographic profile as divided into characteristic plies. If two or more samplings of the one seam have been analysed, after separation into plies the profiles are compared with one another, as with the four profiles of the Barrett seam from the Tomago Coal Measures of New South Wales (Fig. 5.4). Two of the petrographic profiles contain four plies, two contain three. When the sequence of plies is considered, it is apparent that the plies A, B and C in the four sections are rock unit equivalents; and similarly for ply D in the two profiles. The standard profile must contain the maximum number of characteristic plies delineated for the seam, so the Barrett seam standard petrographic profile will contain four plies as shown in Fig. 5.5. Ply D is derived from the average thickness and average microlithotype content of the two original D plies, whilst plies C, B and A are derived similarly from the four original C, B and A plies.

The standard profile now represents the fullest available record of the seam's history, whilst knowledge of the individual contributing profiles shows that the accumulation of the initial ply occurred in a more restricted area than that of the following three plies. Ply D probably has clastic sediment time equivalents in some parts of the depositional area. Plies of limited areal distribution are quite common at the base and/or top of a seam, these characteristic plies may not fulfil the requirements as defined, but they represent abnormal times of deposition, when the sediments were changing from inorganic to organic or conversely.

The standard profile is compiled from as many petrographic profiles of a seam as suitable. Profiles have been compiled for over one hundred Australian seams from the Permian coal measures of New South Wales and Queensland and the Triassic coal measures of Queensland.

TABLE 5.1.

Seams for which a standard profile has been compiled

Permian

New South Wales

Newcastle Coal Measures

1. Wallarah
2. Great Northern
3. Fassifern
4. Wave Hill
5. Victoria Tunnel
6. Dudley
7. Young Wallsend
8. Borehole

Tomago Coal Measures

9. Donaldson
10. Big Ben
11. Rathluba
12. Ravensworth
13. Bayswater
14. Farrells Creek
15. Pikes Gully
16. Arties
17. Liddell
18. Barrett
19. No. 1 (Broke)
20. No. 3 (Broke)
21. Vere

Greta Coal Measures

22. Greta
23. Homeville
24. Brougham Upper
25. Brougham Lower
26. Grasstrees Upper
27. Grasstrees Lower
28. Thiess
29. Puxtrees
30. Balmoral
31. Unspecified Greta

Illawarra Coal Measures

32. Bulli
33. Balgownie
34. Wongawilli
35. Seam from Southern Colliery
36. Tongarra
37. Woonona
38. Lithgow

TABLE 5.1. (cont.)

Queensland

Baralaba Coal Measures

Nipan Area

39. Nipan No. 1
40. Nipan No. 2
41. Nipan No. 3
42. Nipan No. 4
43. Nipan No. 5
44. Nipan No. 6
45. Nipan No. 7
46. Nipan No. 8
47. Nipan No. 9
48. Nipan No. 10

Moura Area

49. Moura A
50. Moura B
51. Moura C
52. Moura D
53. Moura E

Theodore Area

54. Theodore No. 1
55. Theodore No. 2
56. Theodore No. 3
57. Theodore No. 4
58. Theodore No. 5
59. Theodore No. 6
60. Theodore No. 7

Baralaba Area

61. Moody
62. Boyd
63. Cameron
64. Reid
65. Doubtful
66. Dawson
67. Dunstan
68. Double
69. Unnamed

Collinsville Coal Measures

70. Garrick
71. Peace
72. Scott
73. Denison
74. Potts
75. Little Bowen
76. Bowen
77. Blake

TABLE 5.1. (cont.)

Triassic

Queensland

Ipswich Coal Measures (North)

78. Cameron
79. Tantivy
80. Haighmoor (bottoms)
81. Fiery Upper
82. Fiery Lower
83. Eclipse
84. Benley Upper
85. Benley Middles
86. Benley Bottoms

Bundamba Coal Measures

87. Thomas Tops
88. Thomas Bottoms
89. Aberdare
90. Bluff
91. Wright
92. Lagoon
93. Four Foot (tops) ≡ (Wright)
94. Four Foot (bottoms)
95. Bergins (≡ Lagoon)
96. Striped Bacon
97. Rob Roy
98. Cooneans (Uncorrelated)

Callide Coal Measures

99. Marker
100. Callide
101. Sawmill
102. Bottom Upper
103. Bottom Lower

ARTIES SEAM

SCALE: 1FT BORE S6 BC 754

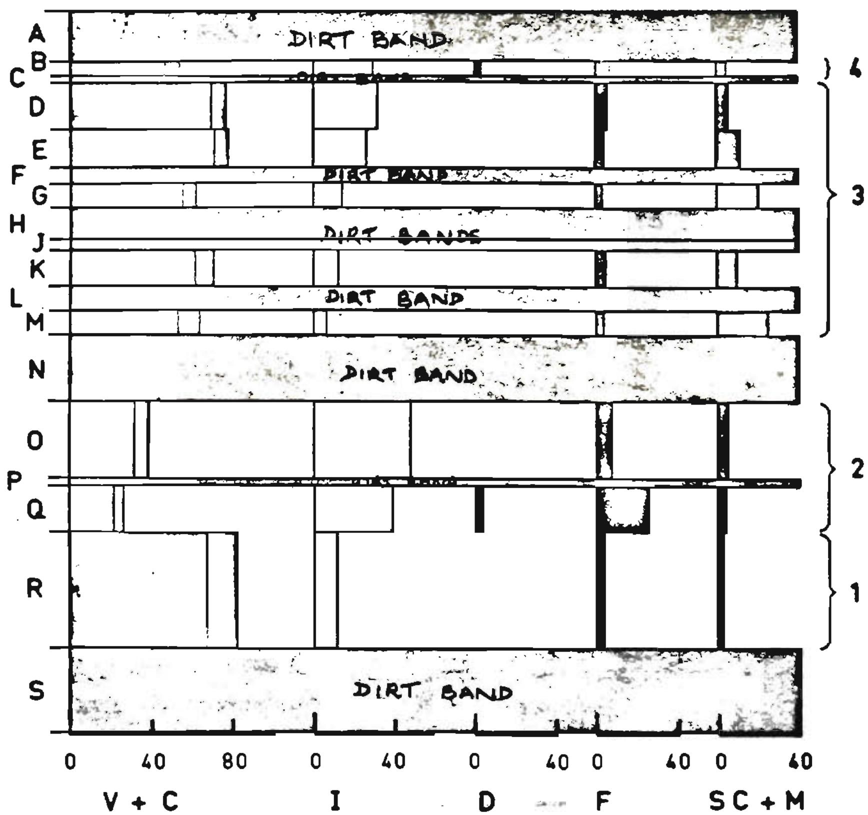


FIG. 5.1

PROFILE OF THE PETROGRAPHIC CONSTITUENTS OF THE ORIGINAL MACROSCOPICALLY DIVIDED SUBSECTIONS

ARTIES SEAM

SCALE: 1FT BORE S6 BC 754

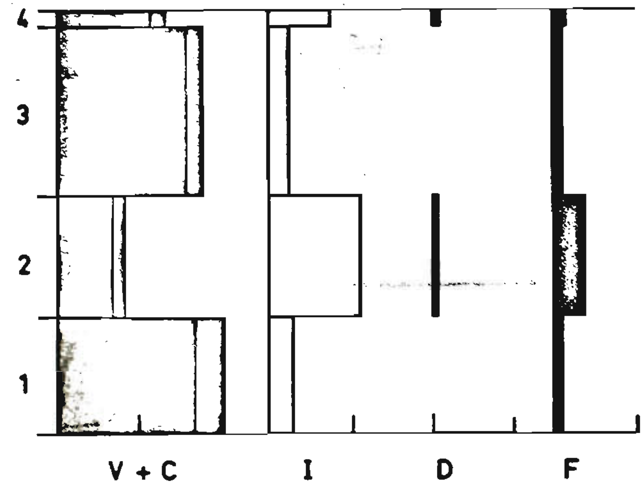


FIG. 5.2

PROFILE OF THE PETROGRAPHIC CONSTITUENTS OF THE CHARACTERISTIC PLIES FORMED FROM THE SUBSECTIONS OF 5.1. DIRT BANDS AND MINERALS OMITTED

V + C - VITRITE + CLARITE Du - DURITE
I - INTERMEDIATES Fu - FUSITE
SC + M - SHALY COAL + MINERALS

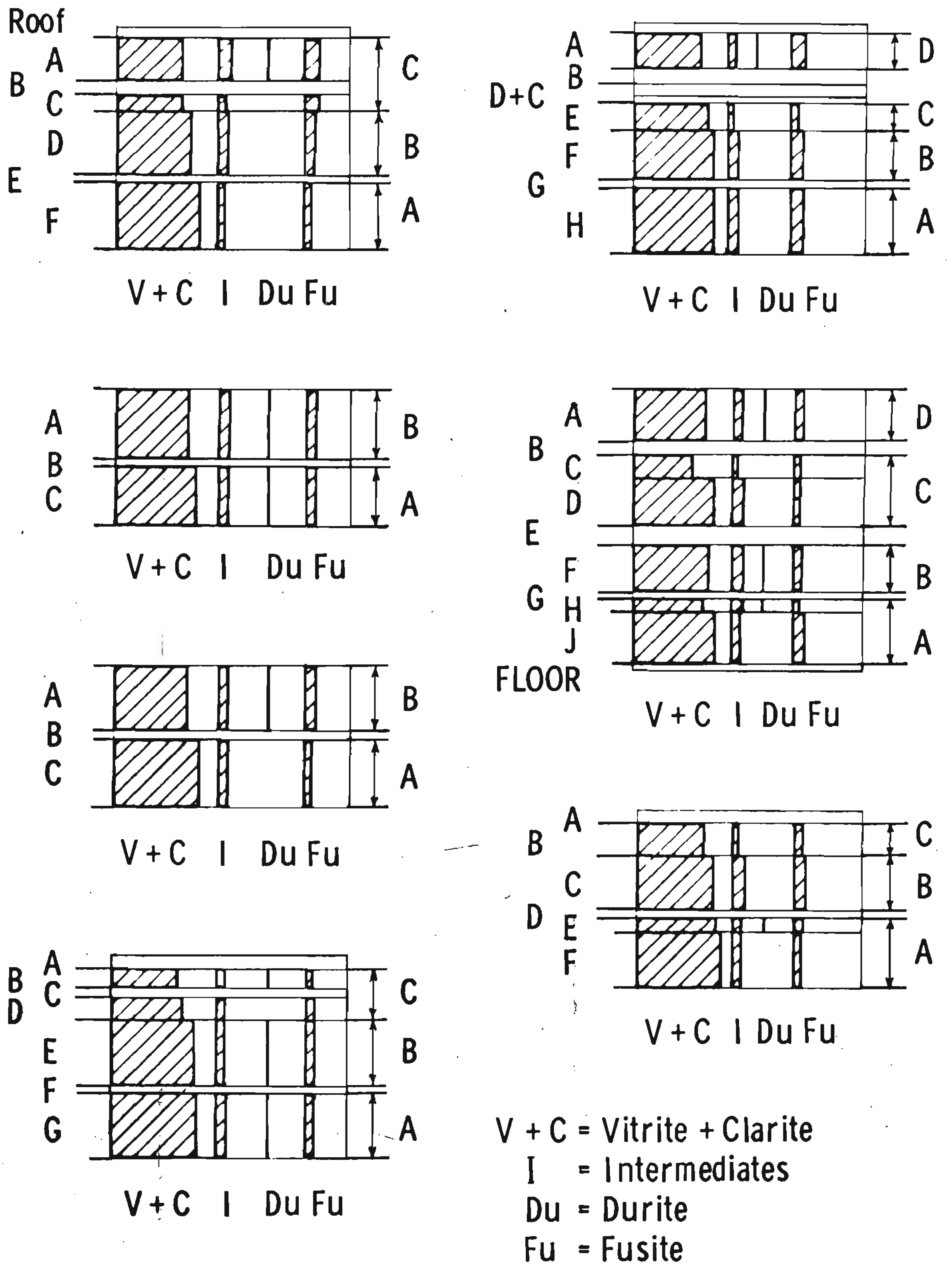


Fig. 5.3. Victoria Tunnel seam Petrographic profiles

VERTICAL SCALE: 10 Feet

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Please see print copy for image

FIG. 5.4 CORRELATION OF CHARACTERISTIC PLIES IN THE BARRETT SEAM

Vertical scale: 10 Feet

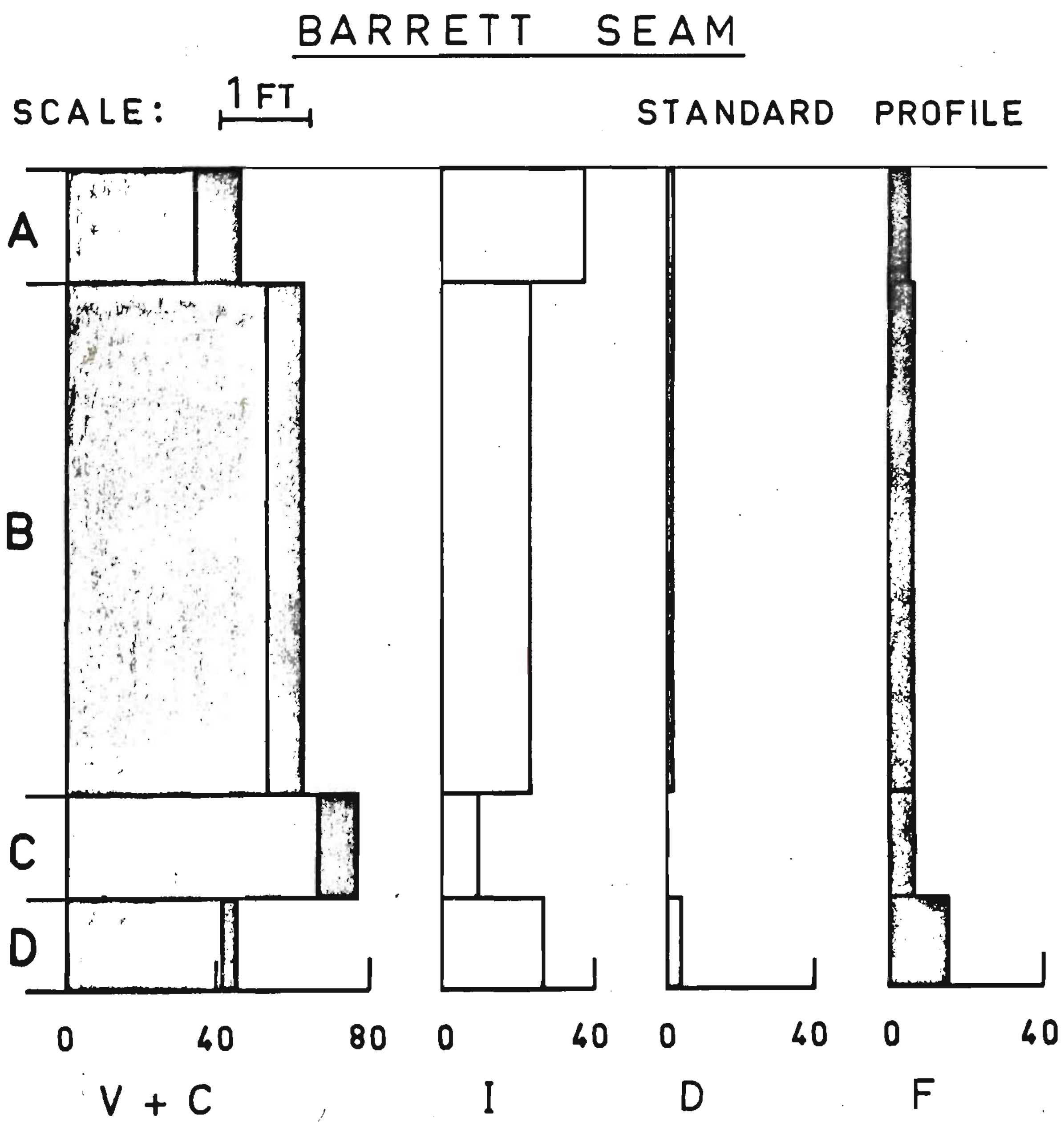

FIG. 5.5. STANDARD PETROGRAPHIC PROFILE COMPILED FROM 4 SEAM SECTIONS

V + C - VITRITE + CLARITE

I - INTERMEDIATES

D - DURITE

F - FUSITE

6. COMPILATION OF TYPE SEAM SEQUENCES

(a) Method

Standard profiles of most of the Permian and Triassic coals from New South Wales and Queensland as listed in Table 5.1 were drawn up. A list and definitions of the types of profiles encountered in these standard profiles is as follows:-

1.	Simple alternating	Alternating vitrite*-rich and vitrite-poor plies, with intermediates, durite and fusite inversely proportional to vitrite.
2.	Complex alternating	Same as (1) but intermediates and fusite not always inversely proportional to vitrite content.
3.	Increasing	Vitrite increases progressively upwards.
4.	Decreasing	Vitrite decreases progressively upwards.
5.	"Greta-like" profile	Three plies of vitrite content decreasing upwards, terminated by a vitrite-rich top ply.
6.	Irregular	Following no common pattern.

Those seams of the same age and from the same and nearby coalfields were compared, as for example seams from the Tomago Coal Measures in the Northern Coalfield (Muswellbrook-Singleton and East

(* vitrite includes any clarite present unless otherwise stated)

Maitland areas) in New South Wales, as shown in Fig. 6.1. Although the proportions of the individual microlithotypes vary between the seams, all but one of them (the Liddell) show the same sequence of petrographic variations in their vitrite contents. The complete, idealized sequence in the majority of the Tomago seams from bottom to top is:-

1. a relatively vitrite-rich ply,
2. a decrease in vitrite from (1), an increase in intermediates, durite and fusite,
3. an increase in vitrite over (2), a decrease in intermediates, durite and fusite,
4. a decrease in vitrite from (3), an increase in intermediates, durite and fusite,
5. a decrease in vitrite and intermediates from (4), an increase in durite and fusite,
6. an increase in vitrite over (5), a decrease in intermediates, durite and fusite (Fig. 6.2).

Not all plies are present in all seams, but those which are present occur in the sequence described (Table 6.1). Where plies of the idealized sequence are missing, the deficiency is either at the top or the bottom (or both) of the seam (Fig. 6.1). The above idealized seam sequence is defined as the "Tomago type seam sequence". (Fig. 6.2.).

The Liddell seam has a simple alternating profile.

The standard petrographic profiles of seams from the Greta, Newcastle, Illawarra, Collinsville, Baralaba (Baralaba, Moura, Nipan and Theodore areas), Ipswich and Callide Coal Measures were examined in the same way as those from the Tomago Coal Measures.

(b) Tomago Coal Measures Type Seam Sequence

See above in "Method" example.

(c) Greta Coal Measures Type Seam Sequence

In Fig. 6.3 are the standard petrographic profiles of ten seams from the Greta Coal Measures from two areas (Maitland-Cessnock and Muswellbrook-Singleton) in the Northern Coalfield of New South Wales. In the Muswellbrook-Singleton area, four out of seven seams have similar standard petrographic profiles, as does an unspecified seam from the Greta Coal Measures (Table 6.2). The corresponding plies in the four standard profiles are numbers 1 to 4, and a Greta Coal Measures type seam sequence has been compiled from the average thicknesses of these plies and their average microlithotype contents (Fig. 6.4). Thus the Greta type seam sequence is a sequence of which the whole or a part is found in more than half of the seams of the same age.

The other three seams, the Brougham Lower, Thiess and Balmoral have irregular, increasing and simple alternating petrographic profiles respectively (Table 6.2).

The profile of the Greta seam in the Maitland-Cessnock area is a simple alternating one. In the lower part of the Homeville seam the profile is an increasing one, the top part of the seam being simple alternating (Table 6.2).

(d) Newcastle Coal Measures Type Seam Sequence

The standard petrographic profiles of eight Newcastle Coal Measure seams analysed from the Northern Coalfield of New South Wales are shown in Fig. 6.5. The Wallarah, Great Northern and Fassifern seams belong to the Moon Island Beach Sub-Group (Johnson, 1969), the other seams to the Lambton Sub-Group (the Wave Hill seam alone belongs to the Adamstown Sub-Group, Branagan and Johnson, 1970) and it can easily be seen that the seams in each sub-group have quite different types of petrographic profiles. The Wallarah and Great Northern seams have complex alternating profiles, the Fassifern an irregular one. In the second group the Wave Hill, Victoria Tunnel, Dudley and Borehole seams have decreasing profiles, making this the predominant type of profile. The Newcastle Coal Measures type seam sequence is therefore taken to be a four ply decreasing one, compiled from the four decreasing seams named (Fig. 6.6). The Young Wallsend seam has a complex alternating profile (Table 6.3).

(e) Illawarra Coal Measures Type Seam Sequence

The standard petrographic profiles of six seams from the Illawarra Coal Measures in the Southern and Southwestern Coalfields of New South Wales are shown in Fig. 6.7. The Bulli, Balgownie, Wongawilli and Tongarra seams have simple alternating profiles, whilst those of the seam from the Southern Colliery and Woonona seams are irregular. Thus the Illawarra type seam sequence is compiled from the four standard profiles of the simple alternating type as previously (Fig. 6.8). (Table 6.4).

(f) Collinsville Coal Measures Type Seam Sequence

The standard petrographic profiles of eight seams from the Collinsville Coal Measures of Upper Permian age in the Collinsville Coalfield of Queensland are shown in Fig. 6.9. Five of the eight seams consist of simply two plies: an upper vitrite-poor and lower vitrite-rich ply. The relationships between these and the other microlithotypes are either simple alternating or complex alternating. (Table 6.5). This two-ply unit is taken to be the Collinsville type seam sequence (Fig. 6.10). The Garrick and Blake seams are considered to be composed of multiples of this unit. More than half of the Bowen seam is alternating; the plies of the uppermost portion are decreasing.

(g) Baralaba Coal Measures Type Seam Sequence

Coals of Upper Permian age have been sampled from numerous localities in the Bowen Basin, Queensland, many of the seams from different areas being considered equivalent to one another (Hawthorne, 1965).

(g (i)) Baralaba Coal Measures: Baralaba Type Seam Sequence

The standard petrographic profiles of nine seams from the Baralaba Coal Measures at Baralaba are shown in Fig. 6.11. Three of the seams, the Boyd, Cameron and Unnamed, have similar profiles and are used to compile an α-type seam sequence (Fig. 6.12), which is a three-ply decreasing sequence in the Cameron and Unnamed seams, but which includes an additional basal vitrite-poor (relatively) ply in the Boyd seam. The α-type seam sequence therefore contains four plies.

Four other seams, the Doubtful, Dawson, Dunstan and Double have profiles similar to one another, and a β-type seam sequence is compiled from these (Fig. 6.13). The β-type sequence is a five-ply simple alternating one. Two seams, the Moody and the Reid, could be fitted into either type sequence, so as an alternative to omitting them from either sequence, they are used in the compilation of both. The seams, in stratigraphical order, are classified in Table 6.6.

(g) (ii) Baralaba Coal Measures: Moura Type Seam Sequence

The standard petrographic profiles of five seams of the Baralaba Coal Measures from the Moura district in Queensland are shown in Fig. 6.14. Four of these, the Moura A, B, C and the upper part of the D seams have similar petrographic profiles, and the Moura type seam sequence is compiled from them (Fig. 6.15). This type sequence is a "Greta-like" profile, plus two upper plies. The lower half of the Moura D seam and the whole of the Moura E seam are simple alternating (Table 6.7).

(g) (iii) Baralaba Coal Measures: Nipan Type Seam Sequence

Six seams of the ten standard petrographic profiles of Baralaba Coal Measure seams from the Nipan district of Queensland are similar (Fig. 6.16). These are the Nipan Nos. 1, 3, 5, 6, 7 and 10 seams, and the Nipan type seam sequence is compiled from them (Fig. 6.17). The Nos. 2, 4 and 8 seams are complex alternating (Table 6.8), and the No. 9 seam is featureless.

(g) (iv) Baralaba Coal Measures: Theodore Type Seam Sequence

In the Theodore area, south of Nipan, seven seams were analysed from the Baralaba Coal Measures, and a Theodore type seam sequence is compiled from the petrographic profiles (Fig. 6.18) of four of them, the Nos. 1, 2, 3 and 7 seams. This type seam sequence (Fig. 6.19) is a four-ply decreasing one. Only the lower halves of the Theodore Nos. 1 and 2 seams are included in the type seam sequence, the upper half of the No. 1 seam is a Greta-like profile, the upper part of the No. 2 seam is increasing. The Nos. 4 and 5 seams are simple alternating (Table 6.9); the No. 6 seam is an α-Baralaba type profile.

(h) (i) Ipswich Coal Measures: Tivoli Type Seam Sequence

Most of the Triassic coals mined in Queensland are from the West Moreton Coalfield and belong to the Ipswich Coal Measures which comprise the Kholo Sub-Group and the Tivoli, Cooneana and Blackstone Formations. The lowermost coal-bearing Formation, the Tivoli, contains twelve major seams, of which six have been analysed (Table 6.10). The petrographic profiles of these are shown in Fig. 6.20. Two of the seams are split, giving nine standard petrographic profiles in all. Five of the seams have similar petrographic profiles - the top of the Cameron, Tantivy, Haighmoor (B), Fiery L/S, Benley (T) and Benley (M), and a type seam sequence is compiled from these. This Tivoli type seam sequence is a Greta-like profile (Fig. 6.21). The lower part of the Cameron seam is initially simple alternating at the base, and then complex alternating in the remainder; The Fiery U/S is simple alternating, the Eclipse complex alternating and the Benley (L), irregular.

(h) (ii) Ipswich Coal Measures: Cooneana Formation

Only one uncorrelated seam from the Cooneana Formation has been analysed, (Table 6.10) and this has a Greta-like profile (Fig. 6.20).

(h) (iii) Ipswich Coal Measures: Blackstone Type Seam Sequence

Nine seams have been analysed from the Blackstone Formation. Some of these are split, and others are considered to be equivalent to one another (Table 6.11). However eleven standard petrographic profiles have been drawn up, as in Fig. 6.22. Six of these have similar profiles, and a Blackstone type seam sequence is compiled from the six seams: the Thomas (T), Aberdare, Lagoon, Four Foot (B), Bergin's and Striped Bacon (Fig. 6.23). The type seam sequence has a Greta-like profile. The Thomas (B), Bluff and Four Foot (T) seams have complex alternating profiles, the Wright, a simple alternating one, and the Rob Roy seam is irregular.

(j) Callide Coal Measures

The standard petrographic profiles of five seams from the Triassic Queensland Callide Coal Measures are shown in Fig. 6.24. The Callide and Bottom (B) seams have complex alternating profiles (Table 6.12), the Marker and Bottom (T) seams have increasing profiles and the Sawmill seam, a decreasing profile. As no one type of profile predominates, and there are three different types represented by the five seams, a type seam sequence could not be chosen for this group of coals.

Thus ten type seam sequences have been compiled for nine groups of Permian coals from New South Wales and Queensland; and two type seam sequences have been compiled for three groups of Triassic coals from Queensland, giving twelve sequences in all.

TABLE 6.1.

Tomago Coal Measures

Seam	No. of samplings in standard profile	Standard profile type
Ravensworth	1	Tomago
Bayswater	3	Tomago
Farrell's Creek	1	Tomago minus 1 top ply
Pikes Gully	1	Tomago minus 1 top ply
Arties	2	Tomago minus 2 top plies
Liddell	3	Simple alternating
Barrett	4	Tomago minus 1 top and 1 bottom ply
Donaldson	1	Tomago minus 1 top and 2 bottom plies
Big Ben	2	Tomago minus 3 top plies
Rathluba	4	Tomago minus 3 top plies
No. 1	1	Tomago minus 1 top and 2 bottom plies
No. 3	1	Tomago minus 2 top plies
Vere	1	Tomago minus 3 top plies

TABLE 6.2.

Greta Coal Measures

Seam	No. of samplings in standard profile	Standard profile type
Greta	8	Simple alternating
Homeville	4	Increasing plus simple alternating
Brougham Upper	1	Greta
Brougham Lower	1	Irregular
Grasstrees Upper	1	Greta
Grasstrees Lower	1	Greta minus 1 top ply
Thiess	2	Increasing
Puxtrees	1	Greta plus 1 extra upper ply
Balmoral	2	Simple alternating
Unspecified	1	Greta

TABLE 6.3.

Newcastle Coal Measures

Seam	No. of samplings in standard profile	Standard profile type
Wallarah	2	Complex alternating
Great Northern	10	Complex alternating
Fassifern	4	Irregular
Wave Hill	1	Newcastle minus 1 top ply
Victoria Tunnel	7	Newcastle
Dudley	1	Newcastle minus 2 bottom plies
Young Wallsend	4	Complex alternating
Borehole	7	Newcastle

TABLE 6.4.

Illawarra Coal Measures

Seam	No. of samplings in standard profile	Standard profile type
Bulli	36	Illawarra
Balgownie	4	Illawarra minus 3 bottom plies
Wongawilli	17	Illawarra minus 1 bottom ply
Seam from Southern Colliery	2	Irregular
Tongarra	6	Illawarra
Woonona	1	Irregular

TABLE 6.5.

Collinsville Coal Measures

Seam	No. of samplings in standard profile	Standard profile type
Garrick	2	Collinsville repeated
Peace	1	Collinsville
Scott	1	Collinsville
Denison	1	Collinsville
Potts	1	Collinsville
Little Bowen	1	Collinsville
Bowen	2	Collinsville repeated twice plus decreasing
Blake	1	Collinsville repeated three times

TABLE 6.6.

Baralaba Coal Measures

Seam	No. of samplings in standard profile	Standard profile type
Moody	1	α or β Baralaba
Boyd	1	α Baralaba
Cameron	1	α Baralaba minus 1 bottom ply
Reid	1	α or β Baralaba
Doubtful	1	β Baralaba minus 2 bottom plies
Dawson	1	β Baralaba minus 1 top ply
Dunstan	1	β Baralaba
Double	1	β Baralaba minus 2 top plies
Unnamed	1	α Baralaba minus 1 bottom ply

TABLE 6.7.

Baralaba Coal Measures: Moura District

Seam	No. of samplings in standard profile	Standard profile type
Moura A	1	Moura minus 4 bottom plies
Moura B	1	Moura
Moura C	4	Moura minus 1 top ply
Moura D (lower half)	1	Simple alternating
Moura D (upper half)	1	Greta-like
Moura E	1	Simple alternating

TABLE 6.8.

Baralaba Coal Measures: Nipan District

Seam	No. of samplings in standard profile	Standard profile type
Nipan No. 1	1	Nipan minus 1 top ply
Nipan No. 2	1	Complex alternating
Nipan No. 3	1	Nipan minus 2 bottom and 1 top plies
Nipan No. 4	1	Complex alternating
Nipan No. 5	1	Nipan minus 1 top and 1 bottom ply
Nipan No. 6	1	Nipan minus 1 bottom ply
Nipan No. 7	1	Nipan minus 1 bottom ply
Nipan No. 8	1	Complex alternating
Nipan No. 9	1	Featureless
Nipan No. 10	1	Nipan minus 1 bottom and 2 top plies

TABLE 6.9.

Baralaba Coal Measures: Theodore District

Seam	No. of samplings in standard profile	Standard profile type
Theodore No. 1	1	Theodore plus Greta-like
Theodore No. 2	1	Theodore plus increasing
Theodore No. 3	1	Theodore minus 1 top ply
Theodore No. 4	1	Simple alternating
Theodore No. 5	1	Simple alternating
Theodore No. 6	1	α Baralaba
Theodore No. 7	1	Theodore minus 2 top plies

TABLE 6.10.

Ipswich Coal Measures: Tivoli and Cooneana Formations

Seam	No. of samplings in standard profile	Standard profile type
Cameron	2	Alternating plus Tivoli
Tantivy	1	Tivoli minus 1 top ply
Haighmoor (B)	1	Tivoli
Fiery U/S	2	Simple alternating
Fiery L/S	2	Tivoli minus 1 bottom ply
Eclipse	1	Complex alternating
Benley (T)	1	Tivoli minus 1 bottom ply
Benley (M)	1	Tivoli minus 1 top and 1 bottom ply
Benley (L)	1	Irregular
Cooneana Formation		
Uncorrelated	1	Greta-like

TABLE 6.11.

Ipswich Coal Measures: Blackstone Formation

Seam	No. of samplings in standard profile	Standard profile type
Thomas (T)	1	Blackstone
Thomas (B)	2	Complex alternating
Aberdare	1	Blackstone plus 1 top ply
Bluff	2	Complex alternating
Wright (= Four Foot)	4	Simple alternating
Lagoon (= Bergins)	3	Blackstone plus 2 top plies
Four Foot (T)	1	Complex alternating
Four Foot (B) (= Wright)	1	Blackstone
Bergins (= Lagoon)	1	Blackstone
Striped Bacon	2	Blackstone minus 2 top plies
Rob Roy	3	Irregular

TABLE 6.12.

Callide Coal Measures

Seam	No. of samplings in standard profile	Standard Profile Type
Marker	1	Increasing
Callide	1	Complex alternating
Sawmill	1	Decreasing
Bottom (T)	1	Increasing
Bottom (B)	1	Complex alternating

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Please see print copy for image

FIG. 6.1 STANDARD PROFILES OF ALL SEAMS STUDIED IN THE TOMAGO SERIES

V VITRITE, C CLARITE, I INTERMEDIATES, Du DURITE, Fu FUSITE

Vertical scale: 10 Feet

Reproduced from Aust. Inst. Min. Met., No. 225, 1968 (Smyth)

Please see print copy for image

FIG. 6.2 AN IDEALIZED TOMAGO SEAM PROFILE

VERTICAL SCALE: 1 Foot

Reproduced from Proc. Aust. Inst. Min. Met., No. 233, 1970 (Smyth).

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Please see print copy for image

FIG. 6.3 STANDARD SEAM PROFILES OF GRETA COALS

V & C - VITRITE-PLUS-CLARITE Du - DURITE
I - INTERMEDIATES Fu - FUSITE
U/S - UPPER SPLIT L/S - LOWER SPLIT

VERTICAL SCALE: 10 Feet

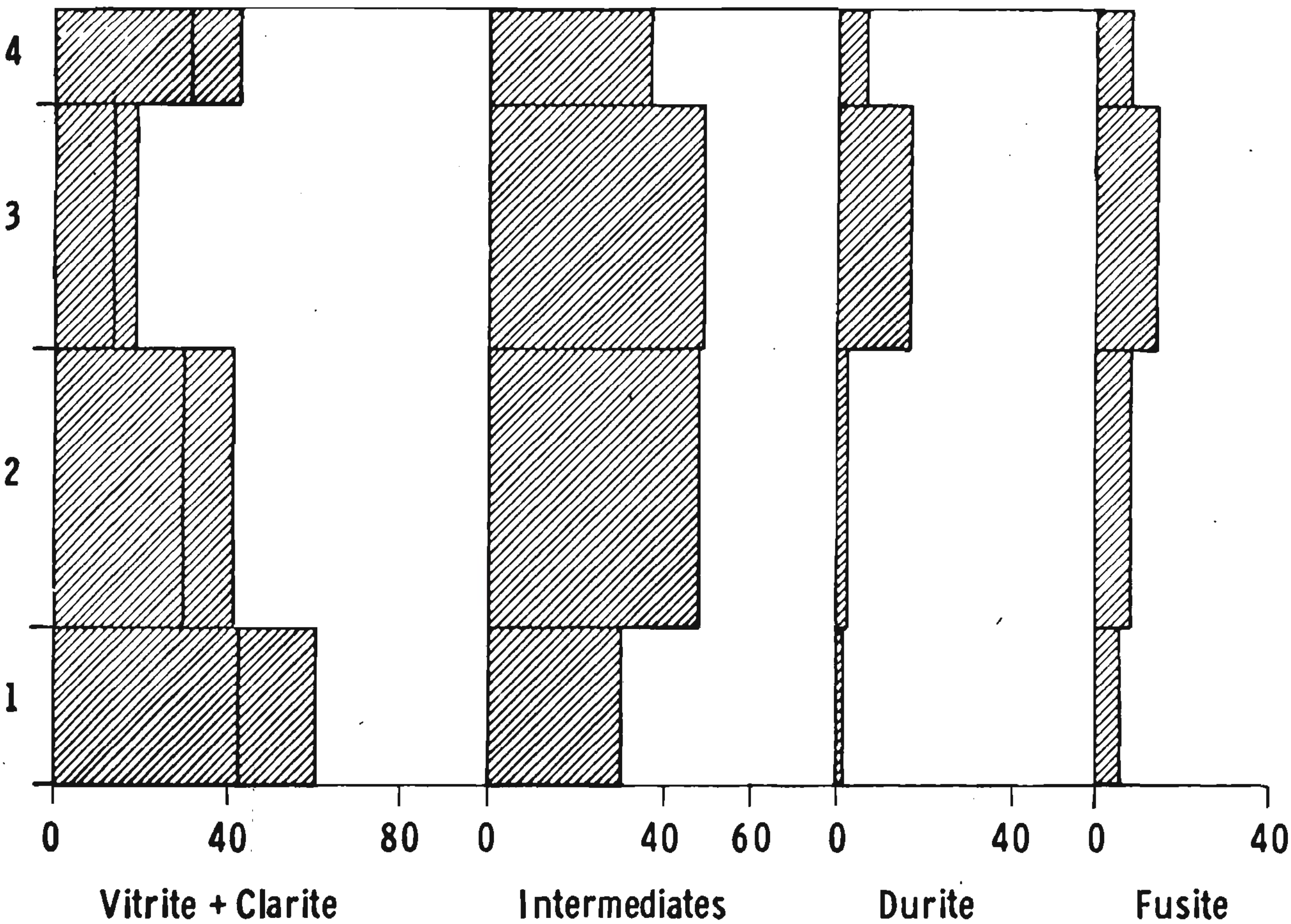


Fig. 6.4. Greta Coal Measures type seam sequence
Compiled from 5 standard profiles

VERTICAL SCALE: 1 Foot

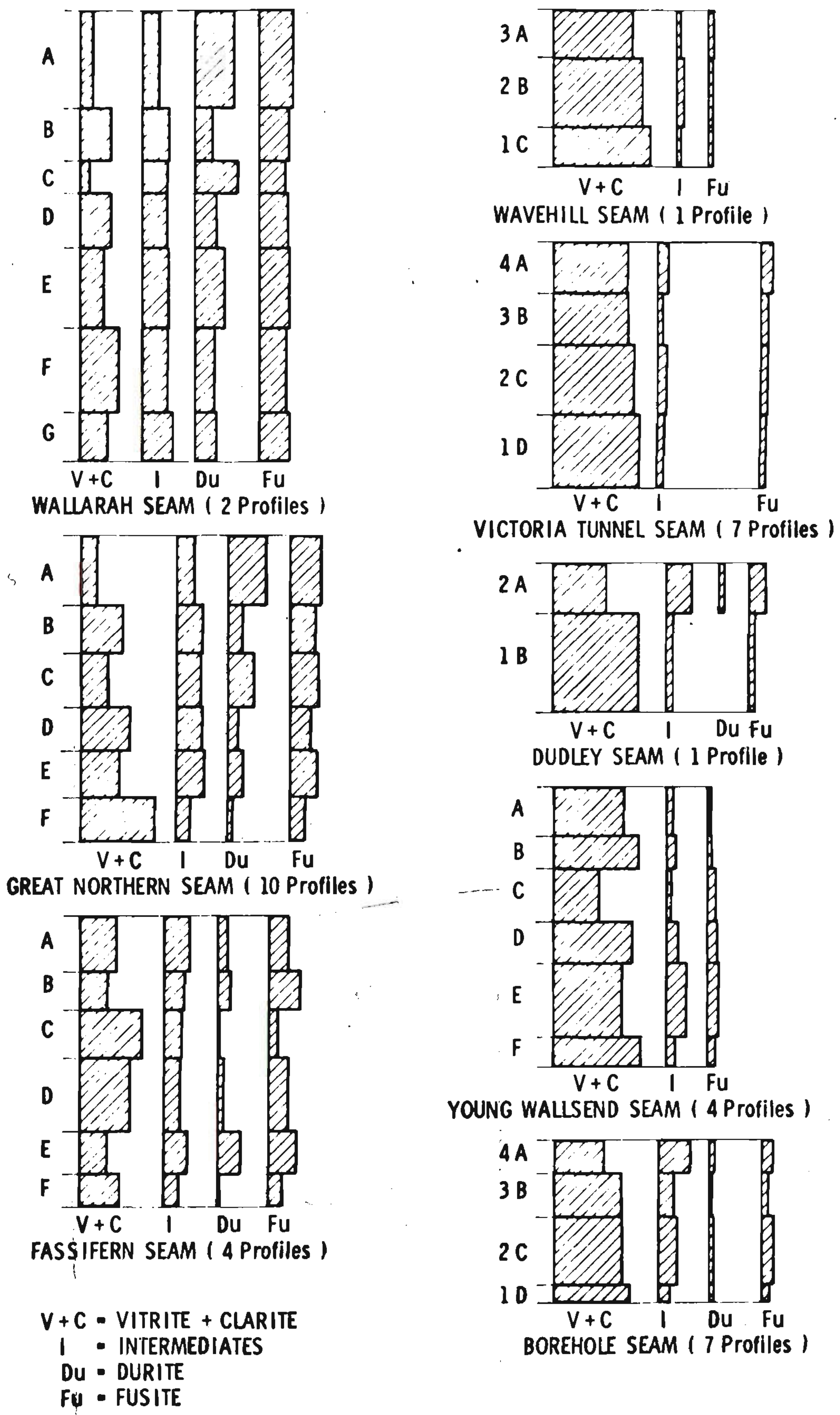


FIG.6.5. STANDARD PROFILES OF SEAMS FROM THE NEWCASTLE COAL MEASURES

VERTICAL SCALE: 10 Feet

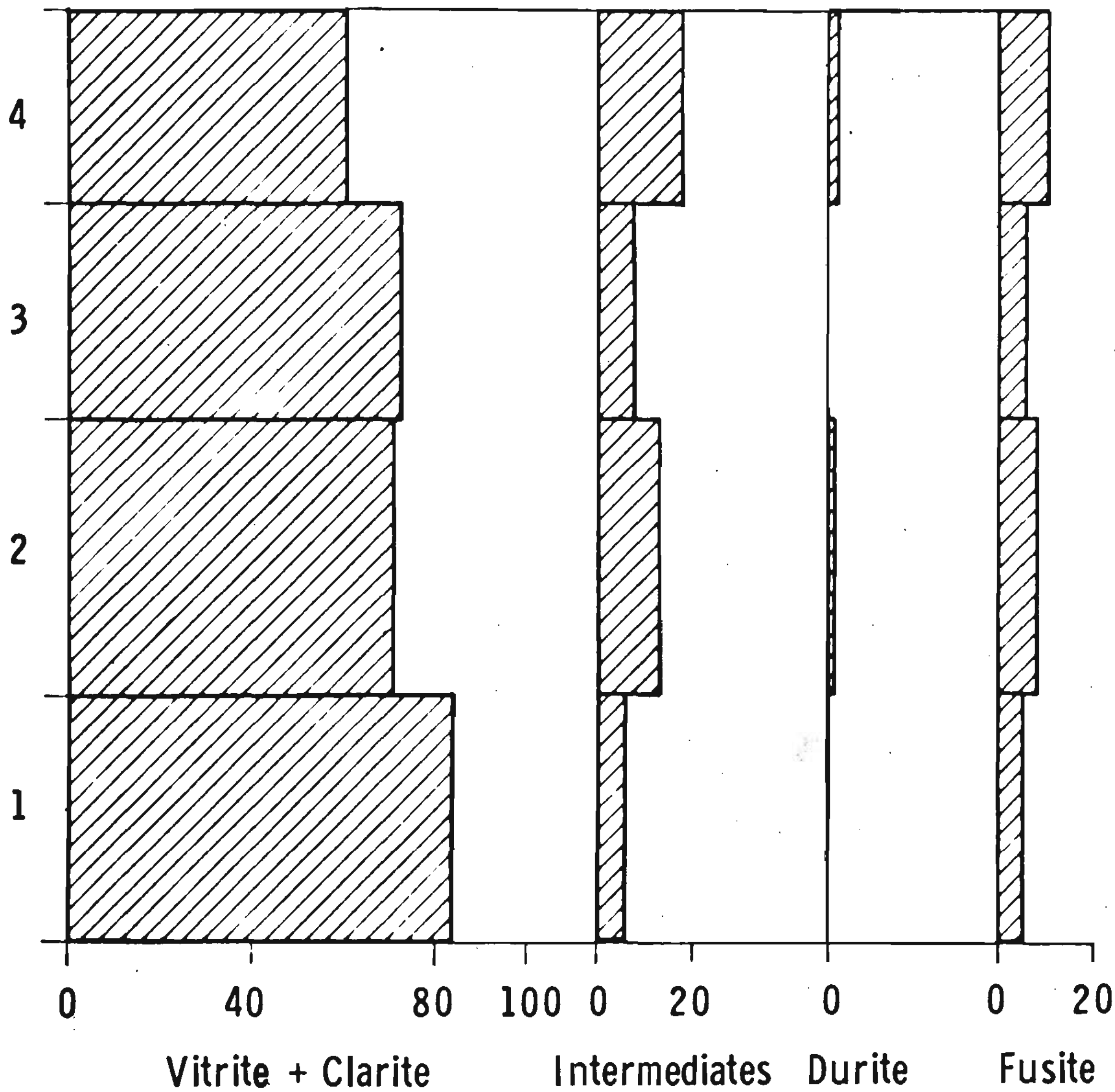


Fig. 6.6. Newcastle Coal Measures type seam sequence
Compiled from 4 standard profiles

VERTICAL SCALE: 1 FOOT

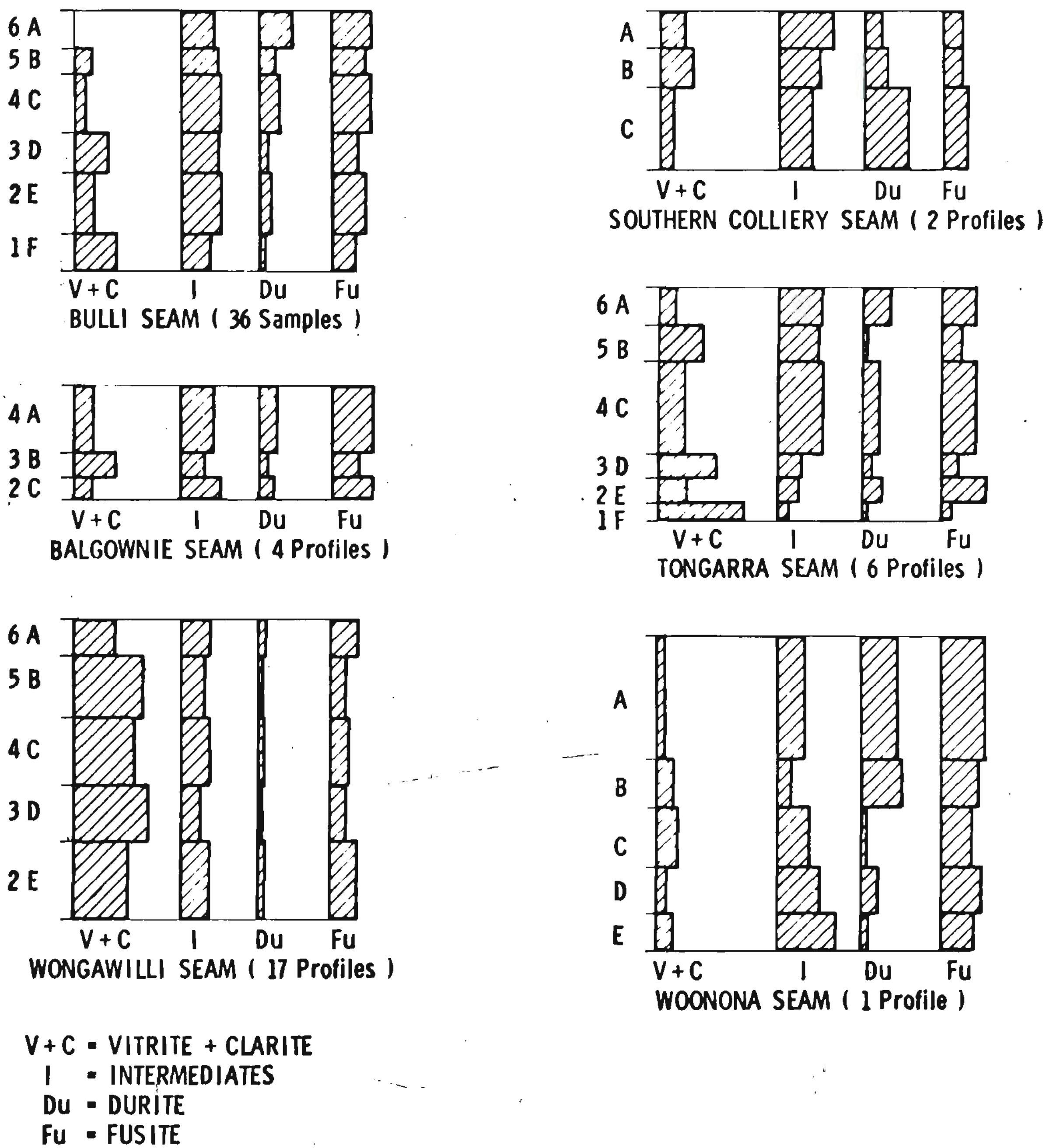


FIG.6.7. STANDARD PROFILES OF SEAMS FROM THE ILLAWARRA COAL MEASURES

VERTICAL SCALE: 10 Feet

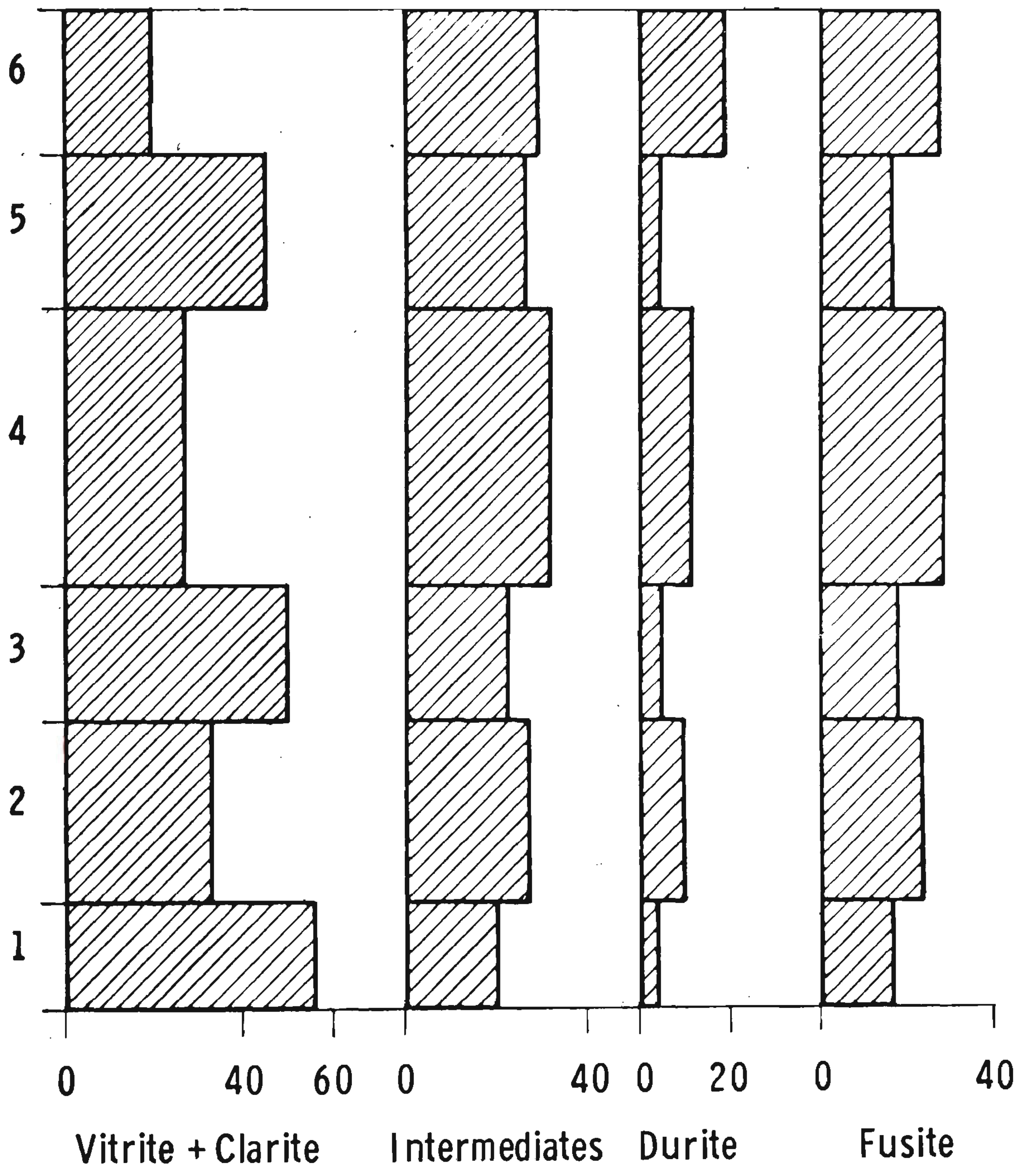
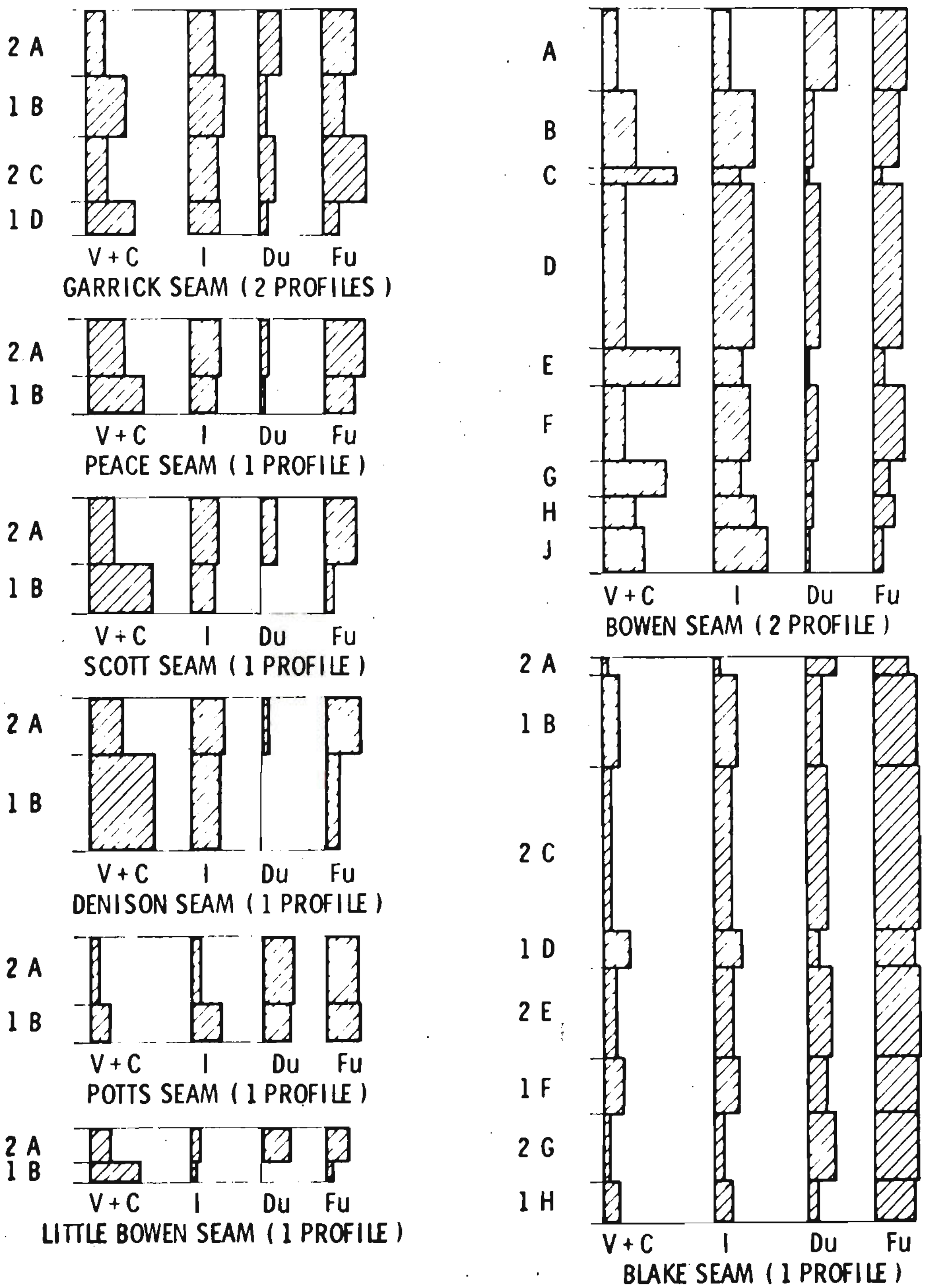


Fig. 6.8. Illawarra Coal Measures type seam sequence

Compiled from 4 standard profiles

Vertical scale: 1 Foot



V + C = VITRITE + CLARITE
I = INTERMEDIATES
Du = DURITE
Fu = FUSITE

FIG.6.9. STANDARD PROFILES OF SEAMS FROM THE COLLINSVILLE COAL MEASURES

VERTICAL SCALE: 10 Feet

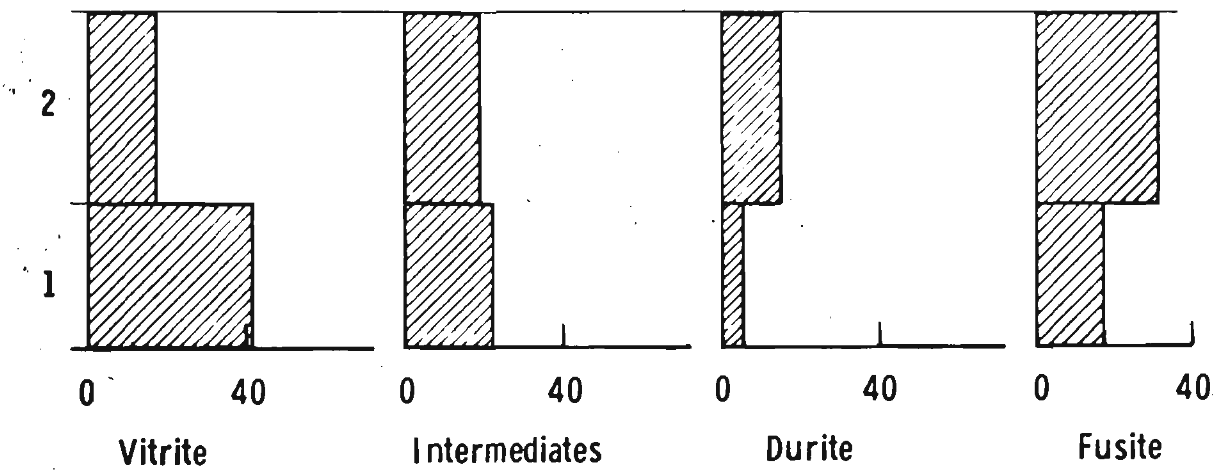
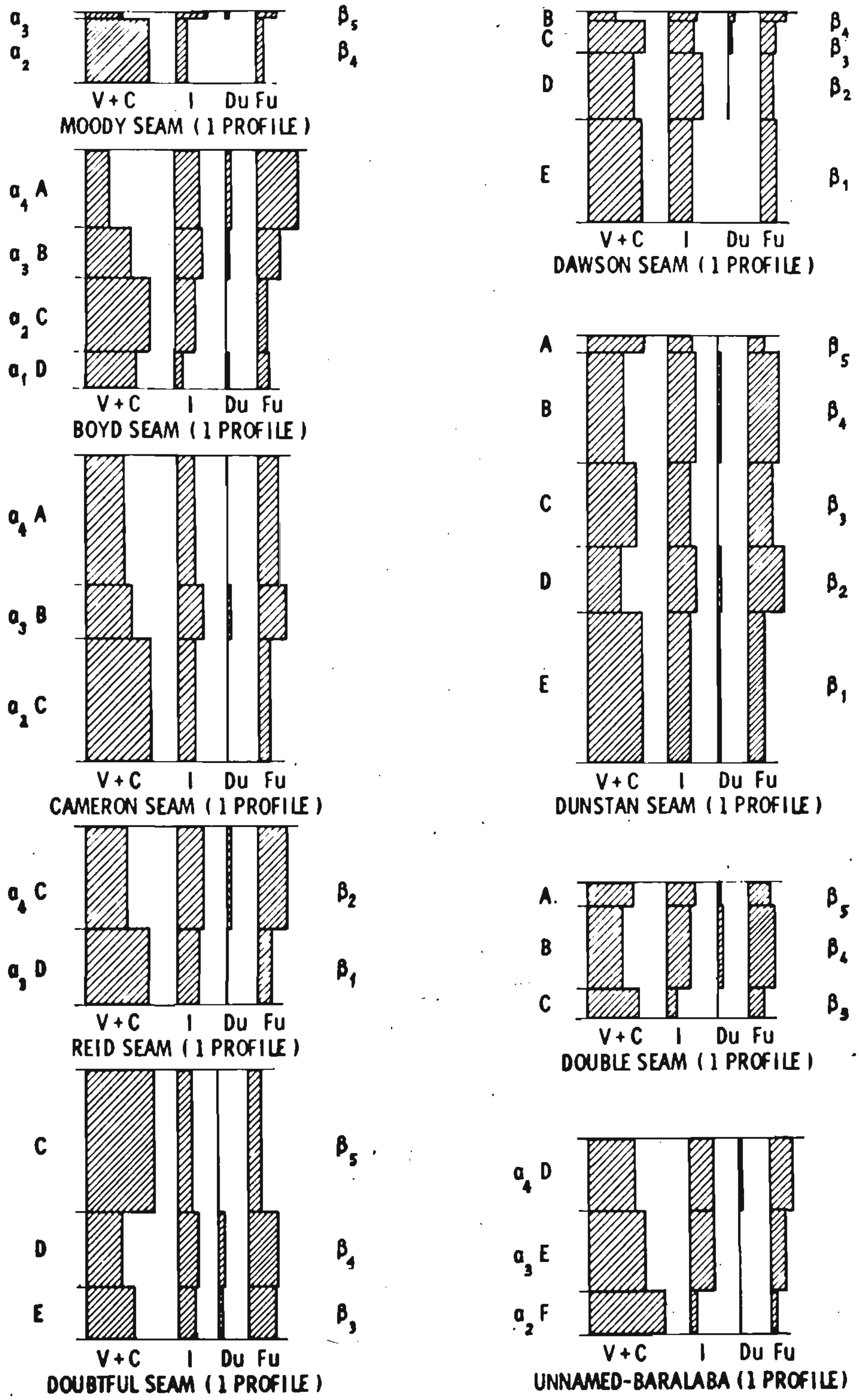


Fig. 6. 10. Collinsville Coal Measures type seam sequence
Compiled from 8 standard profiles

VERTICAL SCALE: 1 Foot



V + C = VITRITE + CLARITE
I = INTERMEDIATES
Du = DURITE
Fu = FUSITE

FIG.6.11. STANDARD PROFILES OF SEAMS FROM THE BARALABA COAL MEASURES AT BARALABA

VERTICAL SCALE: 10 Feet

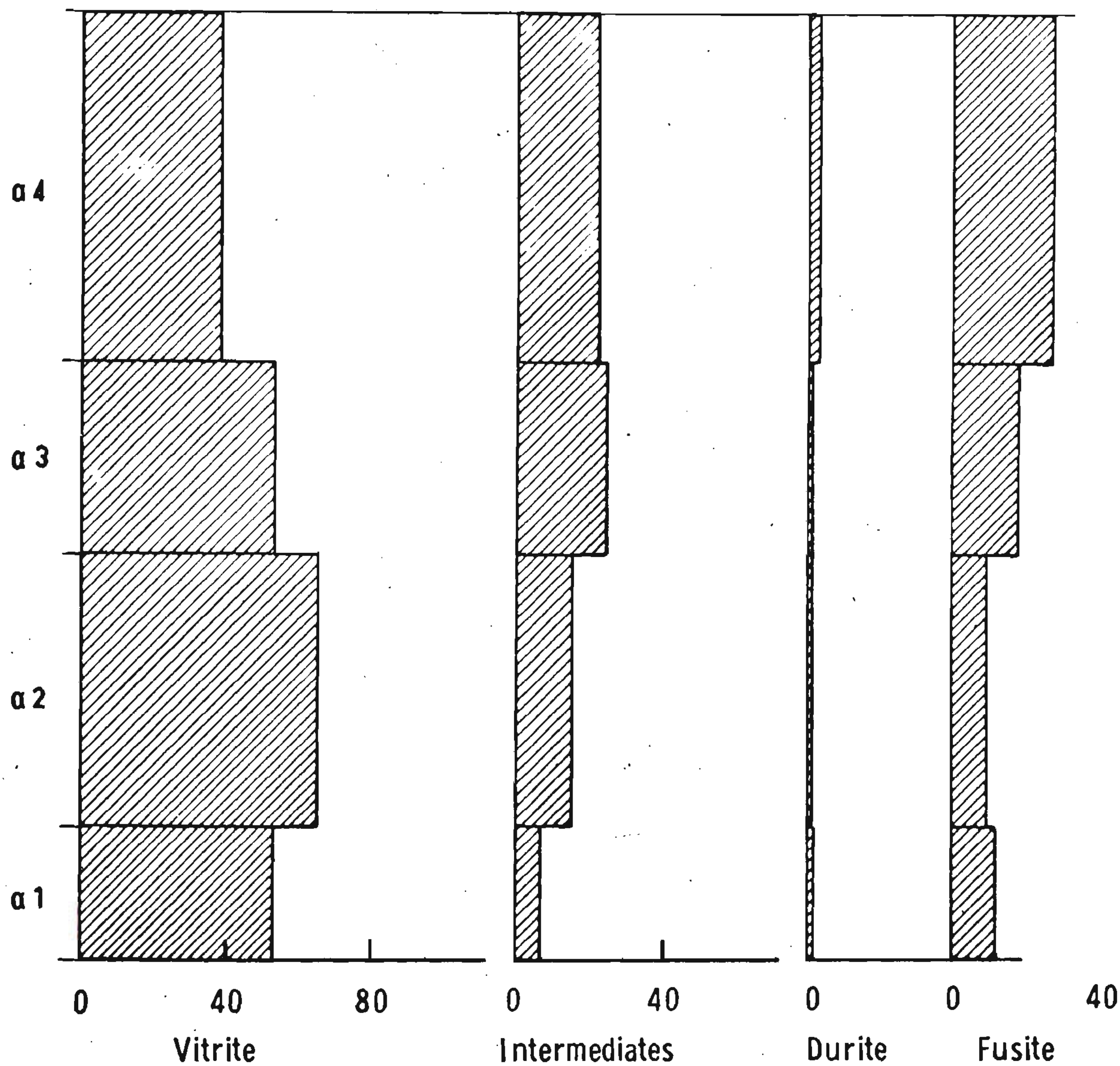
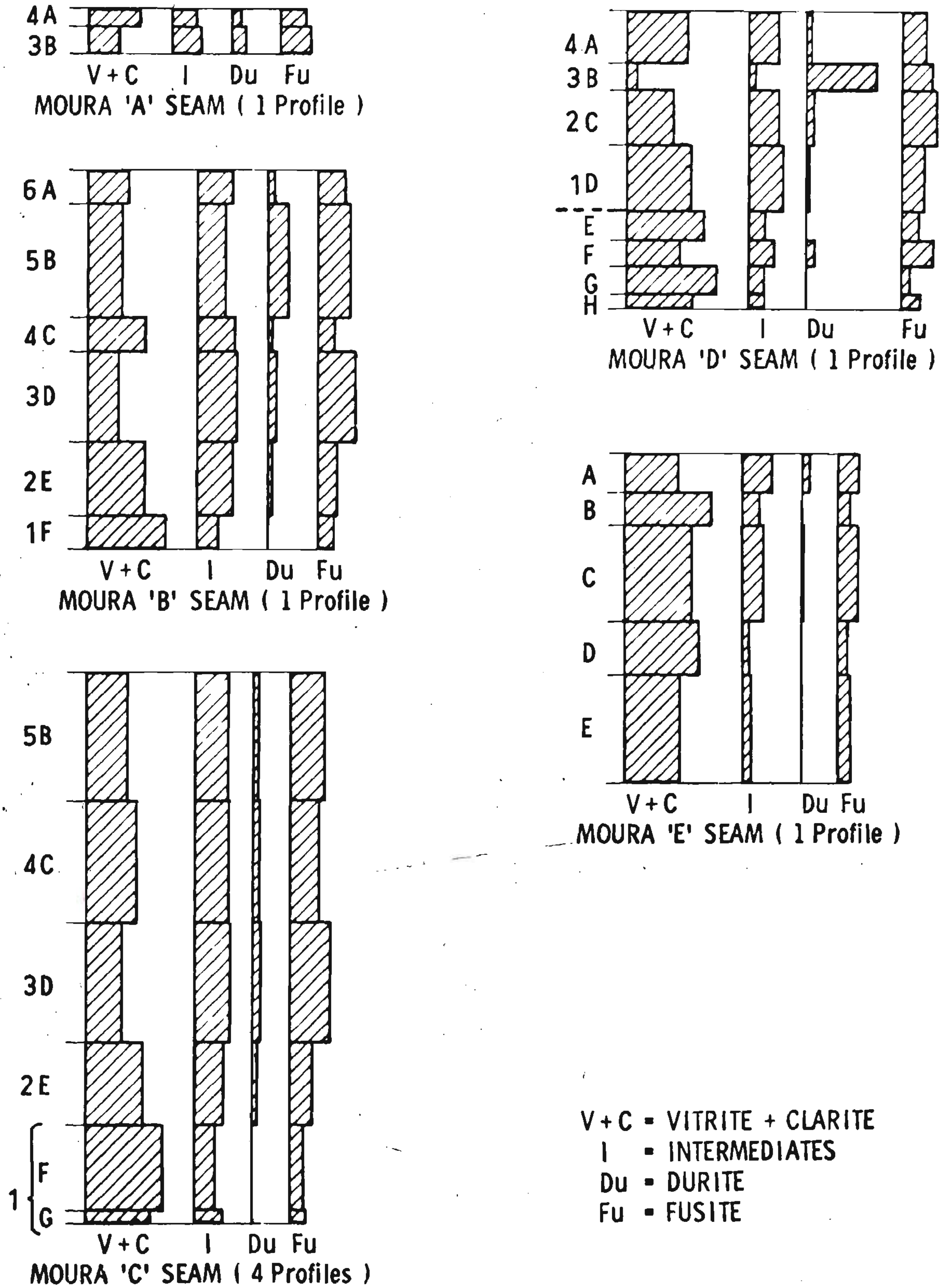


Fig. 6. 12. Baralaba Coal Measures type seam a sequence
Compiled from 5 standard profiles

Vertical scale: 1 Foot

Fig. 6. 13. Baralaba Coal Measures type seam β sequence
Compiled from 6 standard porfiles

Vertical scale: 1 Foot



V + C = VITRITE + CLARITE
I = INTERMEDIATES
Du = DURITE
Fu = FUSITE

FIG.6.14. STANDARD PROFILES OF SEAMS FROM THE BARALABA COAL MEASURES, MOURA DISTRICT

VERTICAL SCALE: 10 Feet

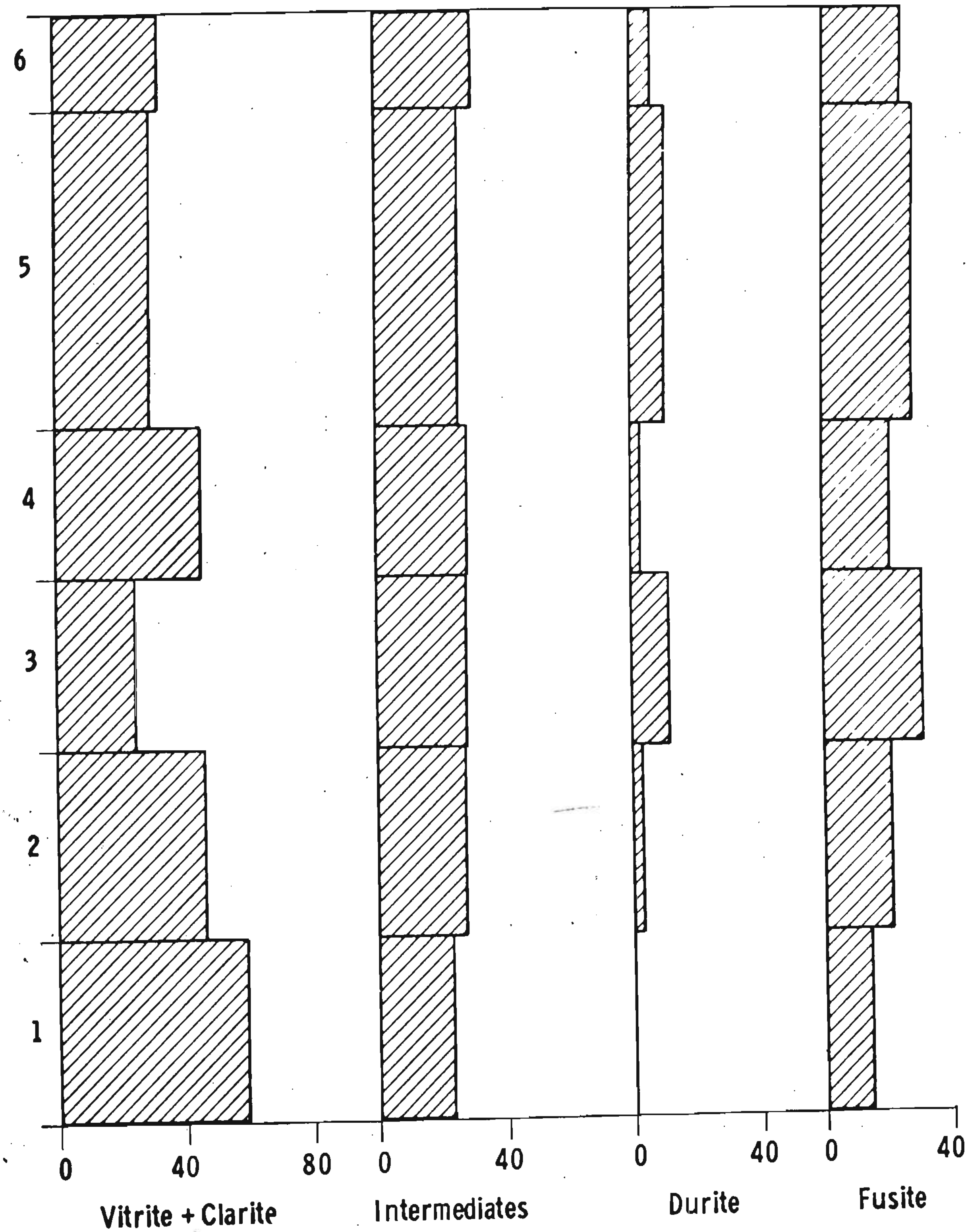


Fig. 6. 15. Moura type seam sequence
Compiled from 4 standard profiles

Vertical scale: 1 Foot

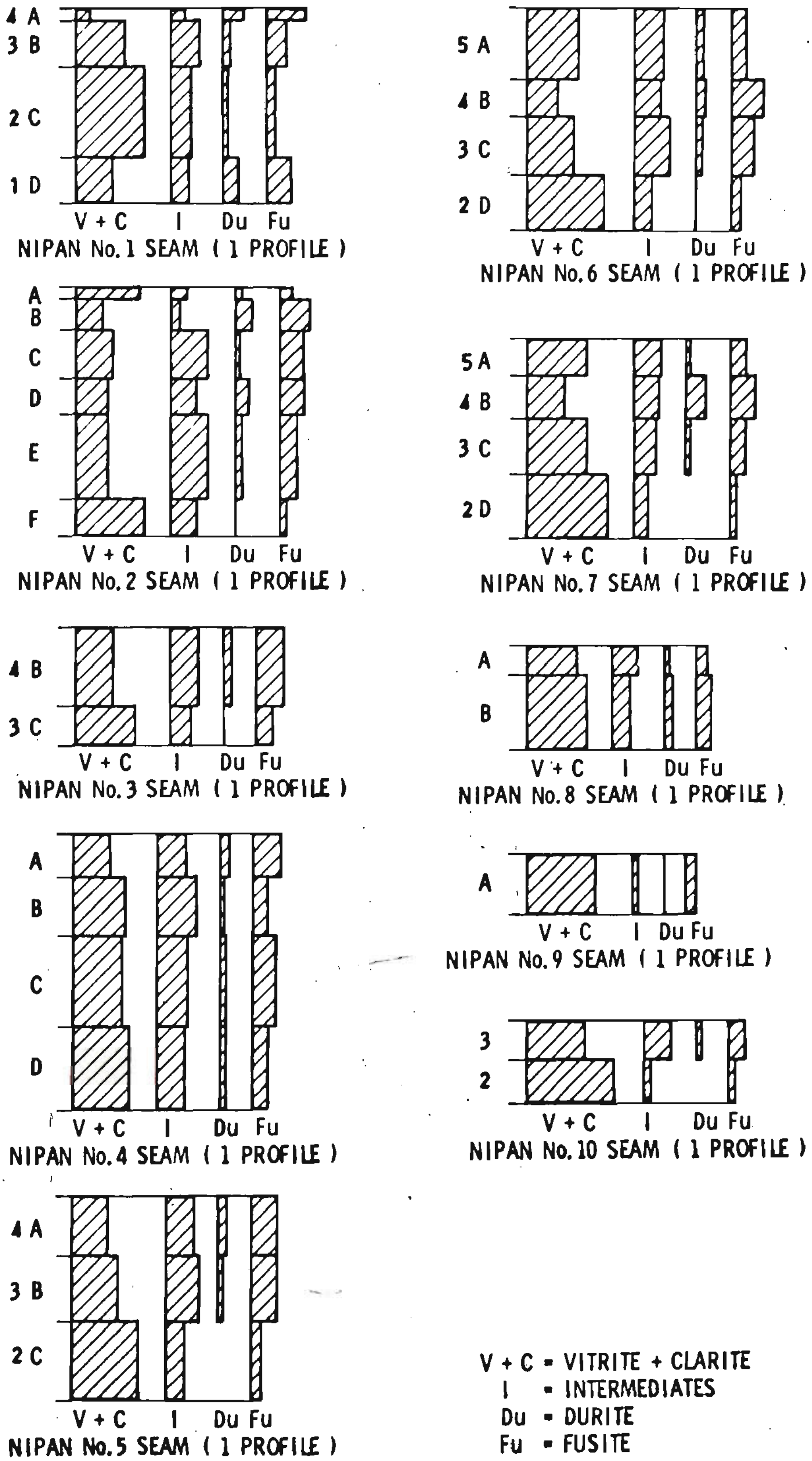


FIG. 6.16. STANDARD PROFILES OF SEAMS FROM THE BARALABA COAL MEASURES NIPAN DISTRICT

VERTICAL SCALE: 10 Feet

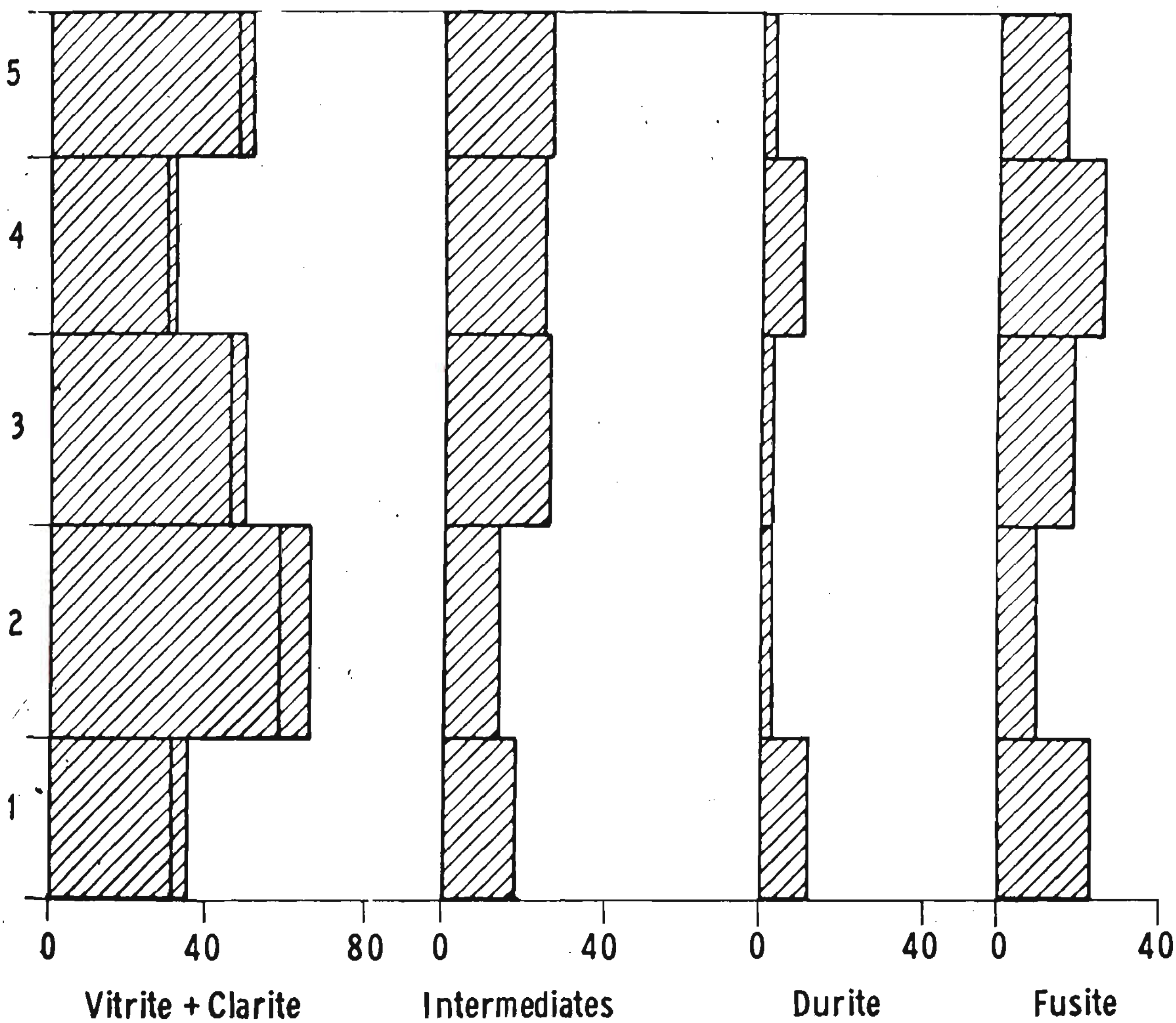


Fig. 6. 17. Nipan type seam sequence
Compiled from 6 standard profiles

Vertical scale: 1 Foot

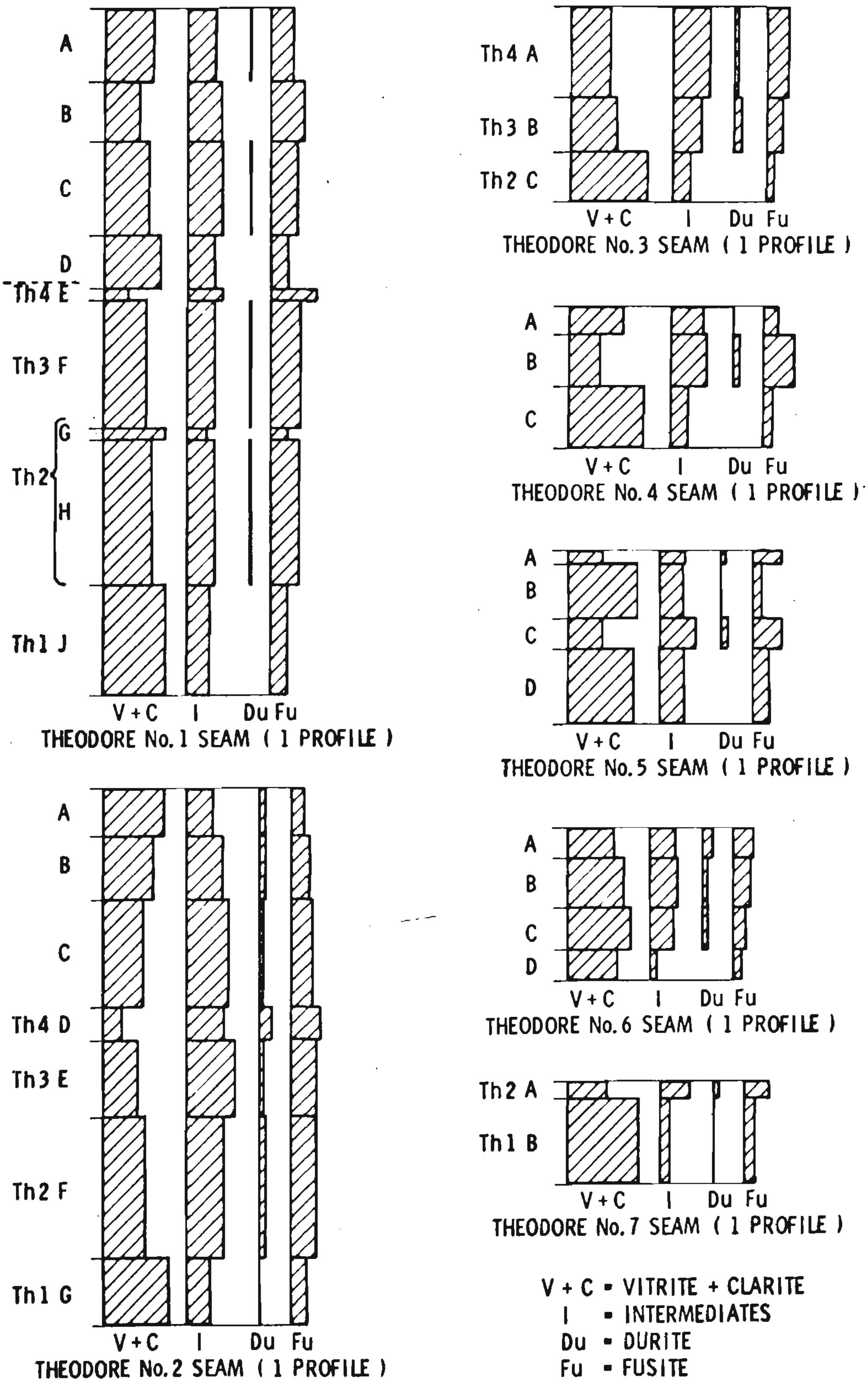


FIG. 6.18. STANDARD PROFILES OF SEAMS FROM THE BARALABA COAL MEASURES, THEODORE DISTRICT

VERTICAL SCALE: 10 Feet

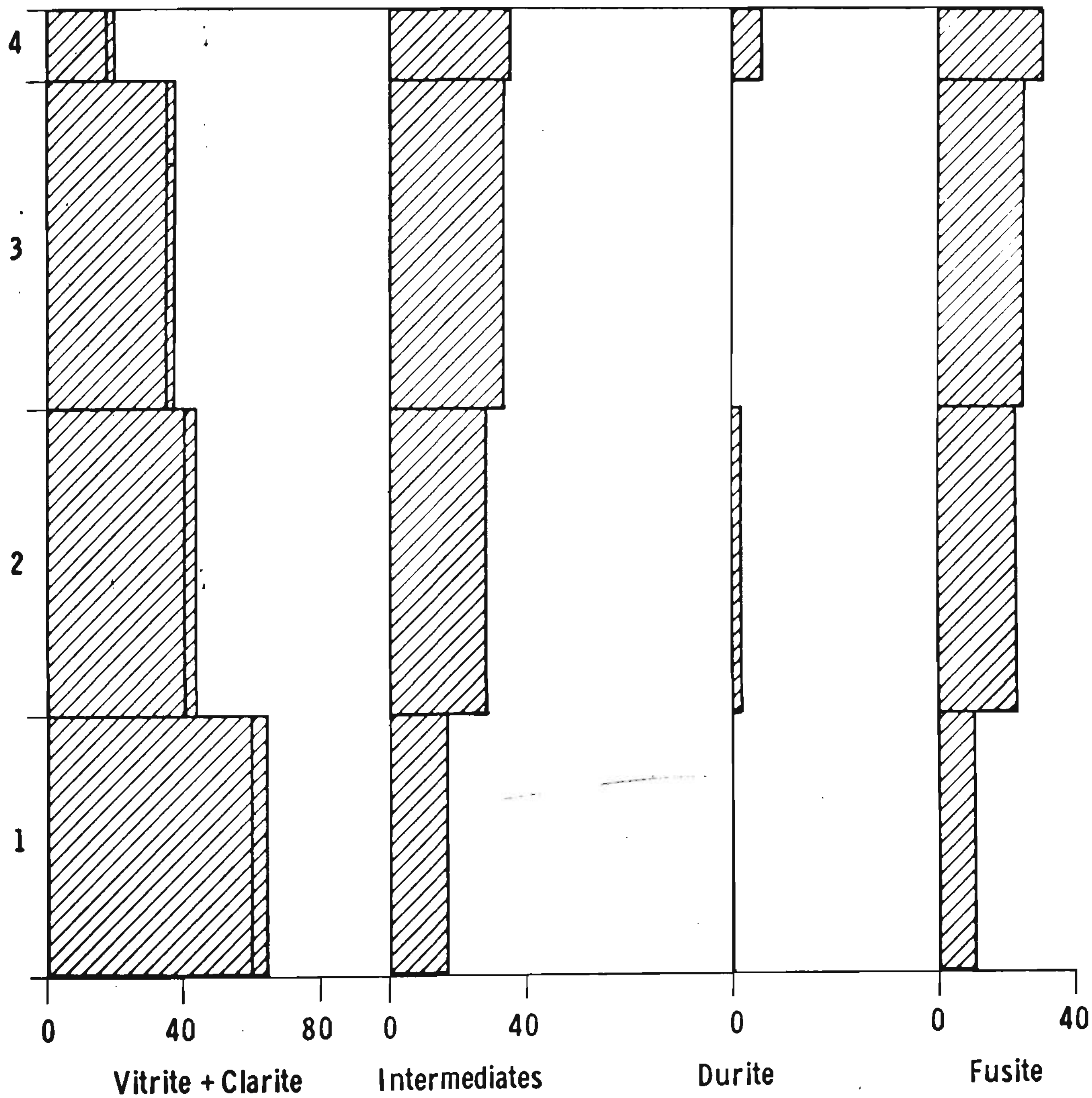
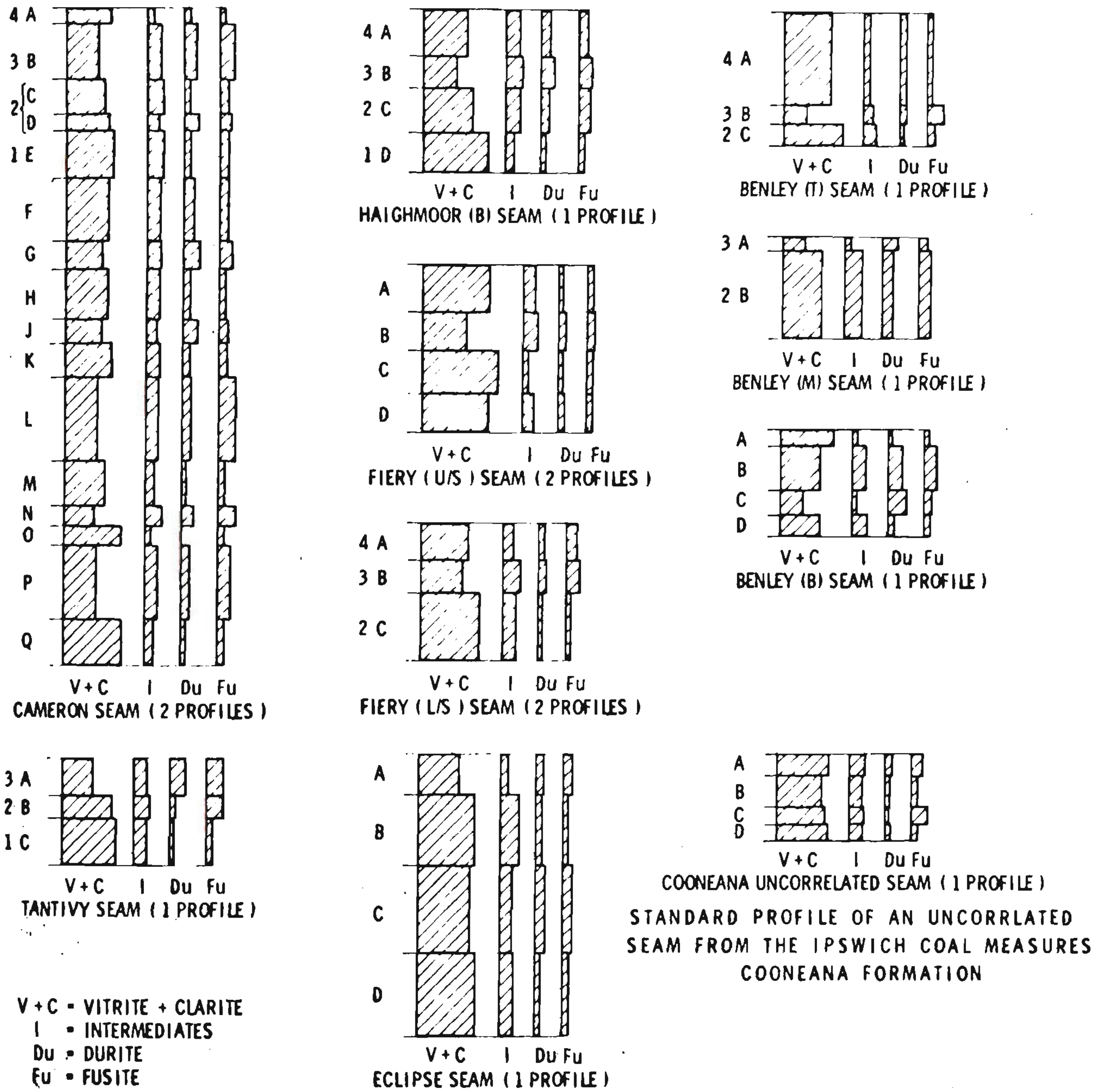


Fig. 6. 19. Theodore type seam sequence
Compiled from 4 standard profiles

Vertical scale: 1 Foot



STANDARD PROFILE OF AN UNCORRLATED SEAM FROM THE IPSWICH COAL MEASURES COONEANA FORMATION

FIG.6.20. STANDARD PROFILES OF SEAMS FROM THE IPSWICH COAL MEASURES, TIVOLI FORMATION

VERTICAL SCALE: 10 Feet

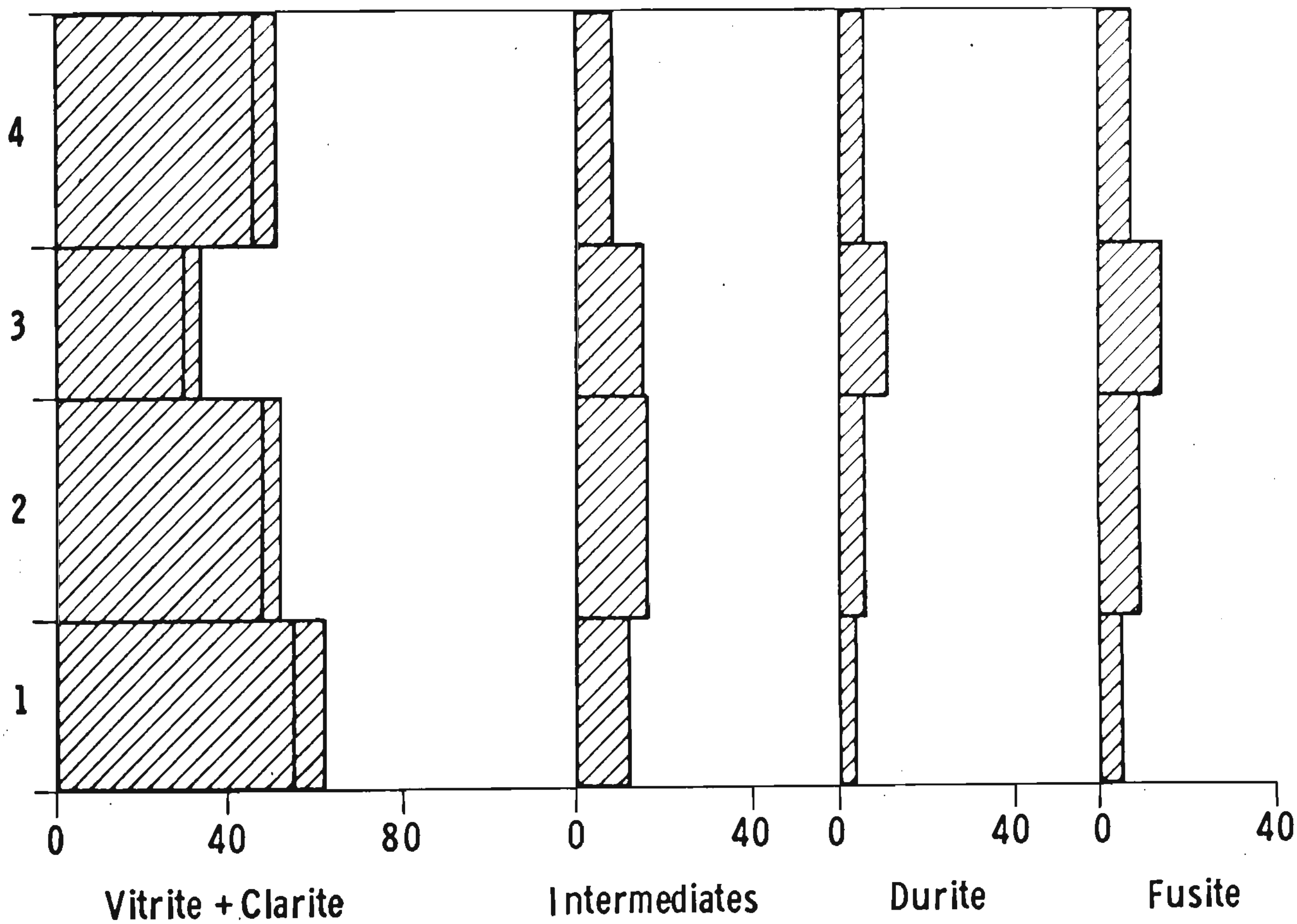


Fig. 6.21. Tivoli type seam sequence
Compiled from 6 standard profiles

Vertical scale: 1 Foot

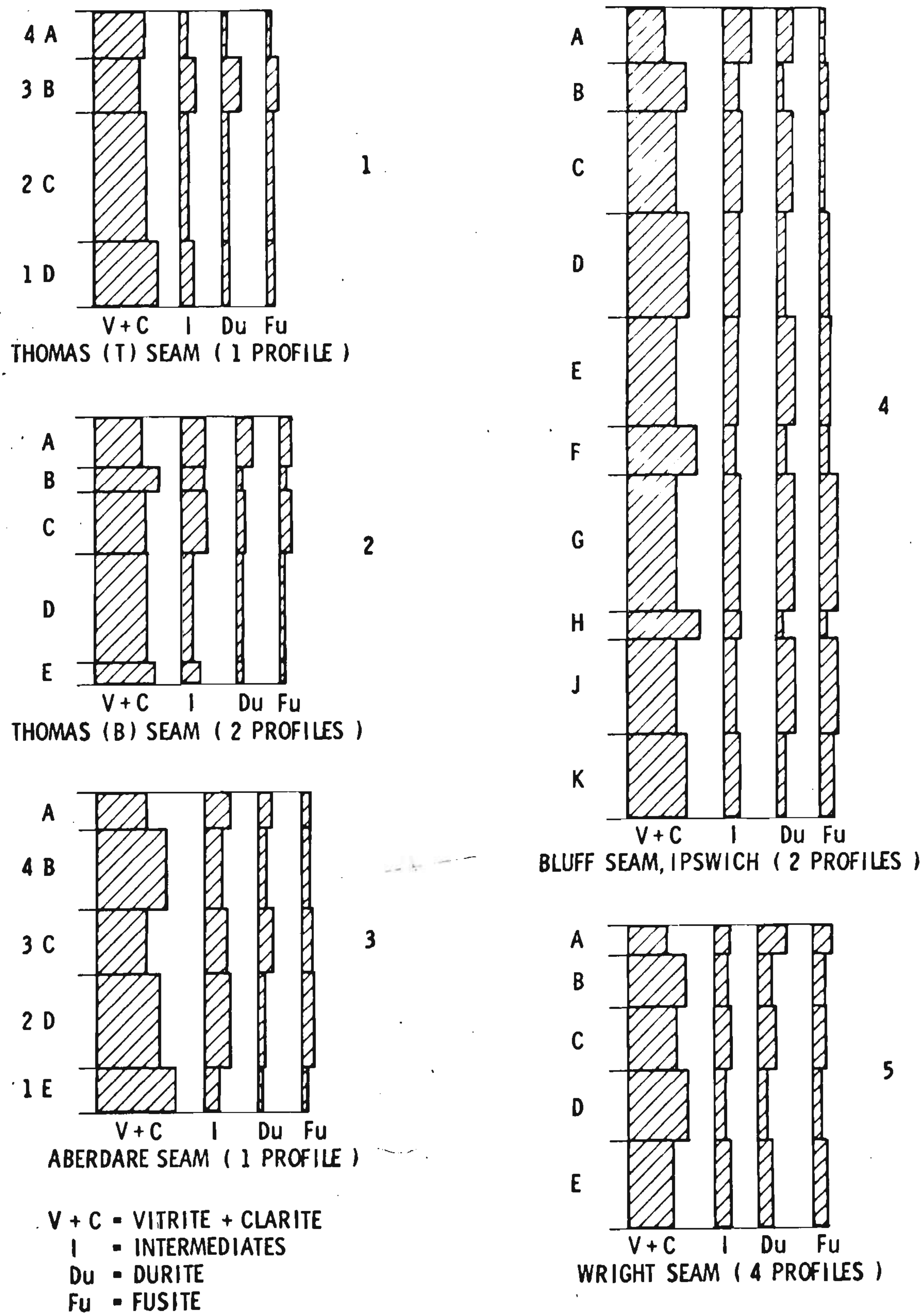


FIG.6.22. STANDARD PROFILES OF SEAMS FROM THE IPSWICH COAL MEASURES, BLACKSTONE FORMATION

(CONT'D ON NEXT PAGE)

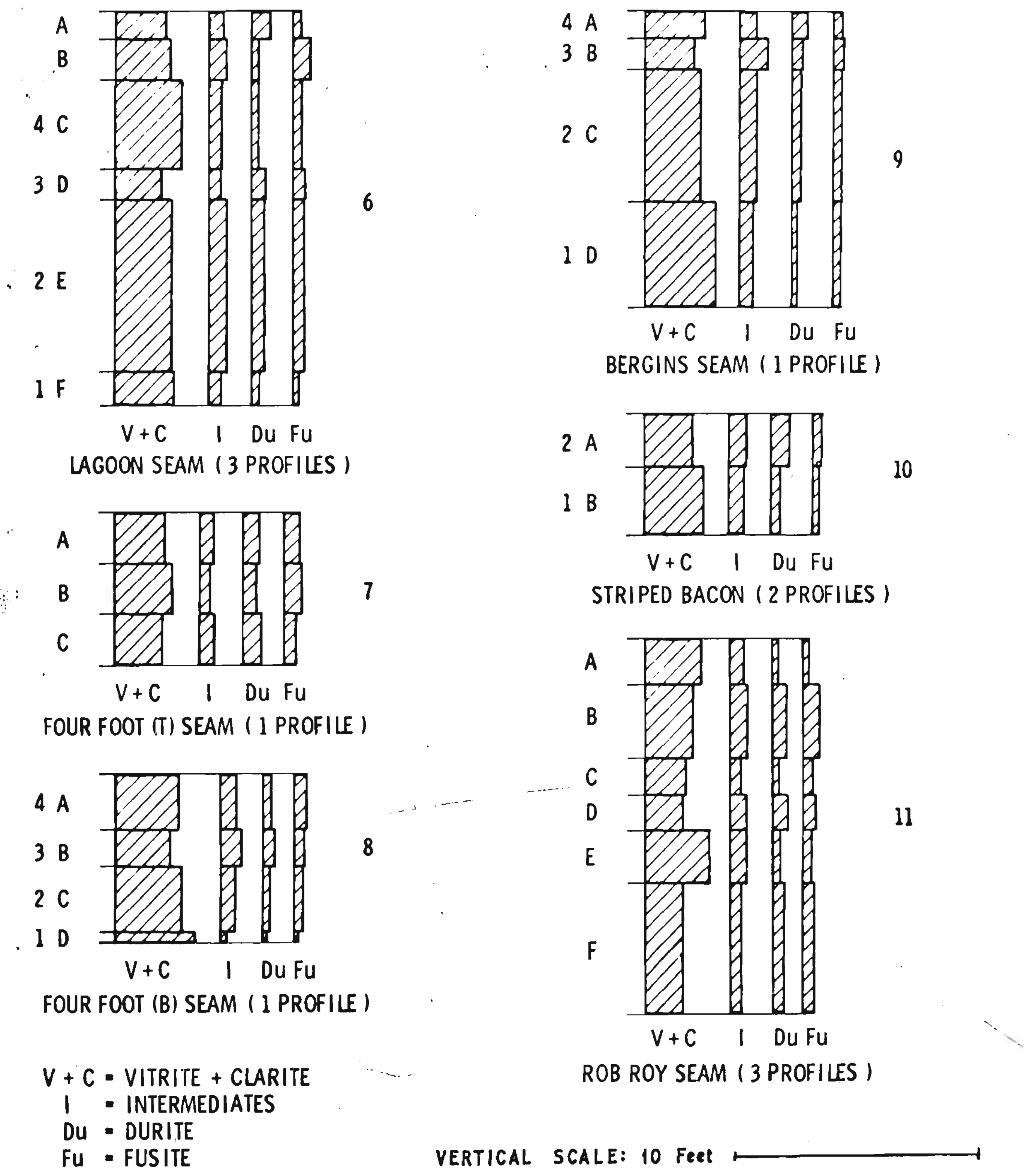


FIG. 6.22. STANDARD PROFILES OF SEAMS FROM THE IPSWICH COAL MEASURES, BLACKSTONE FORMATION

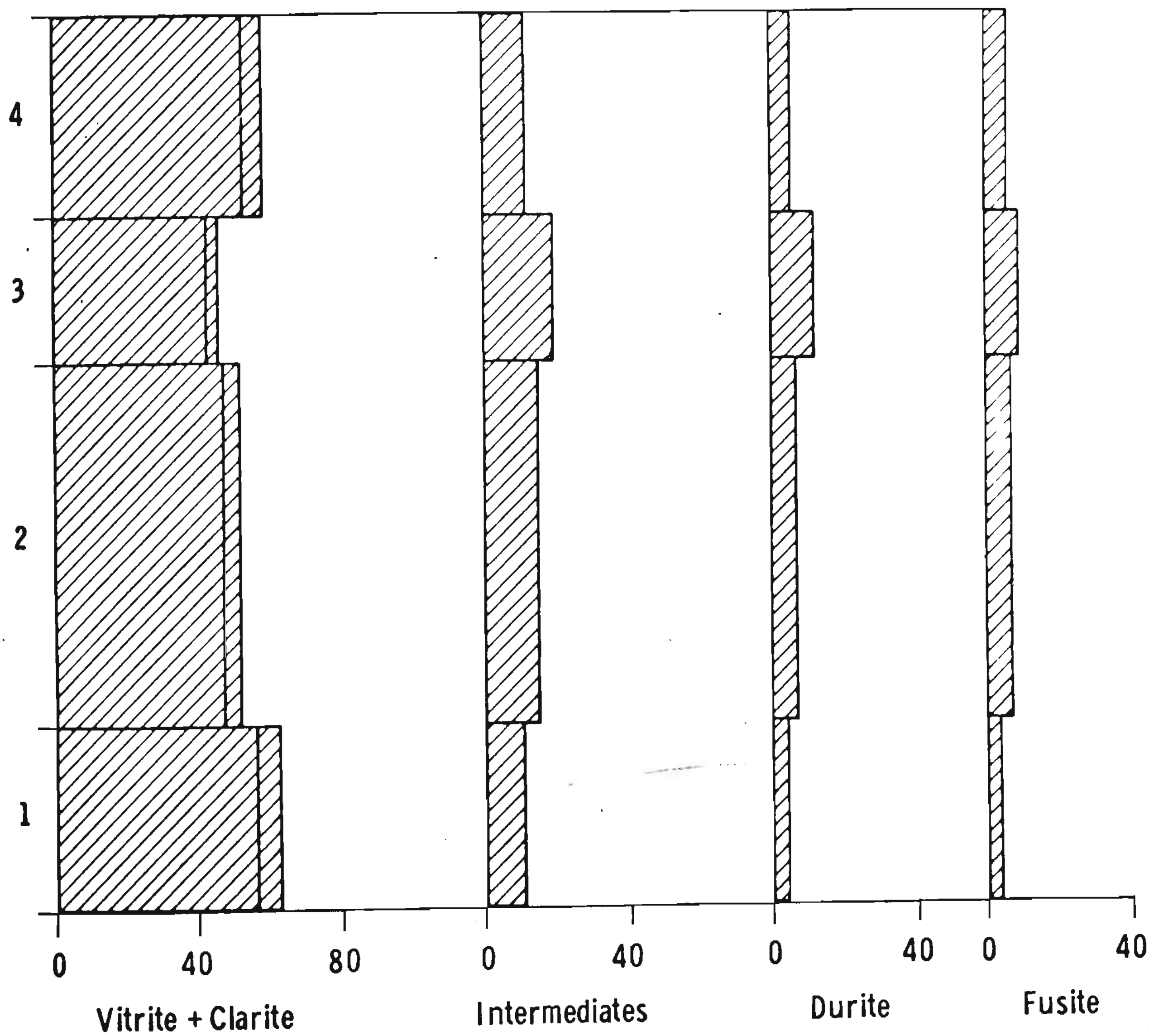


Fig. 6.23. Blackstone type seam sequence
Compiled from 6 standard profiles

Vertical scale: 1 Foot

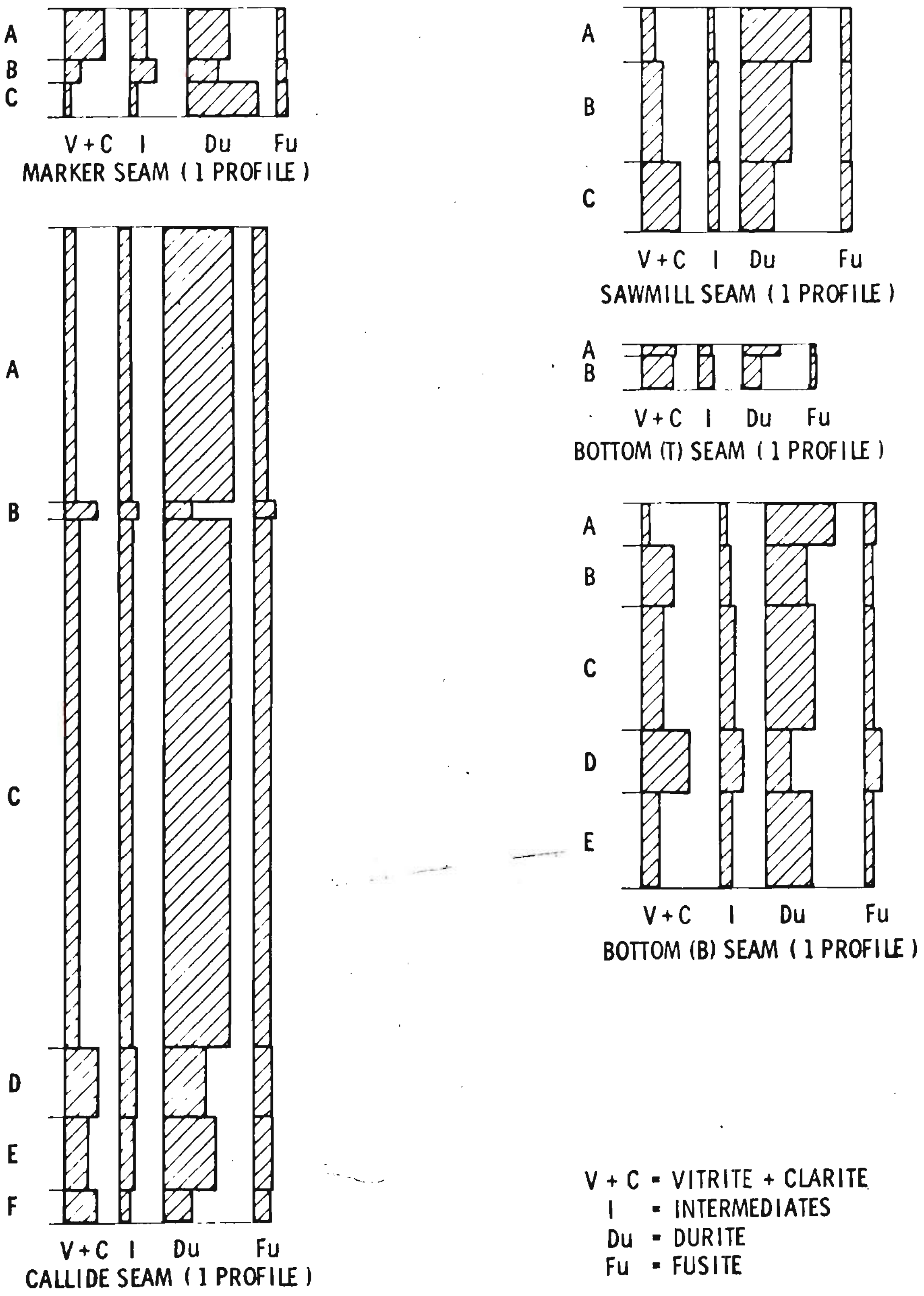


FIG. 6.24. STANDARD PROFILES OF SEAMS FROM THE CALLIDE COAL MEASURES

VERTICAL SCALE: 10 Feet

7. COMPARISON OF TYPE SEAM SEQUENCES AND THEIR DERIVATION FROM BASIC SEQUENCES

Type seam sequences for the Tivoli, Blackstone, Greta, Tomago, Moura, Nipan, α- and β- Baralaba, Theodore, Illawarra, Newcastle and Collinsville coals, twelve in all, are shown in Fig. 7.1. The petrographic profile of the Greta type seam sequence (c) is very similar to

(i) the four plies of the Tivoli and Blackstone type seam sequences, (a) and (b), respectively;

(ii) the top four plies (Nos. 3 to 6) of the Tomago type seam sequence (d);

(iii) the bottom four plies (Nos. 1 to 4) of the Moura type seam sequence (e); and

(iv) the top four plies (Nos. 2 to 5) of the Nipan type seam sequence (f).

Table 7.1 gives the ratios of the changes in microlithotype content of the relevant plies of these six type seams in ascending numerical order.

Several of the seams at Moura are thought to be equivalent to various seams at Baralaba (Hawthorne, 1965) and seams in the Nipan and Theodore areas may also be equivalent to seams at Baralaba and Moura. From Fig. 7.1 (g), it is seen that the three top plies (Nos. 2-4) of the Baralaba α- type seam sequence are similar to the three bottom plies (Nos. 1-3) of the Moura type seam, and that the five plies of the Baralaba β- type seam (h) are similar to the five top plies (Nos. 2-6) of the Moura type seam. That is, on the basis of these profiles any of the seams from Baralaba could be equivalent to seams at Moura, which is not inconsistent with Hawthorne's views on correlation between the two areas. The ratios of changes in microlithotype contents of the relevant plies of the Baralaba β and Moura type seams are given in Table 7.2.

The bottom three plies of the Theodore type sequence (Nos. 1-3) are similar in vitrite plus clarite and fusite contents to the Moura (plies 1-3), Nipan (plies 2-4) and α-Baralaba (plies 2-4) type seam sequences.

Overall, some degree of similarity amongst at least nine of the type sequences can be shown (Fig. 7.1, a to j). What has emerged from the investigation is not, as was thought likely by the author, a priori, that coal seams of various ages and from different areas of sedimentation are different, but that they have many features in common. Not only are coals from different coal measures within the Permian similar, but these Permian coals also resemble Triassic ones. Details given by Smith (1962) for Westphalian Yorkshire coals suggest a resemblance to Carboniferous coals as well.

Fig. 7.2 is a schematic representation of all the possible ways in which the vitrite plus clarite (or any other microlithotypes) contents of seams with from two to six plies may vary. The hatched configurations are those which occur among the one hundred and one profiles of seams listed in Tables 6.1 through to 6.12. Of the sixty-two possible ways in which coal seams with two to six plies may develop, only twenty-four occur among the Permian and Triassic coals studied. Seven of these twenty-four are single occurrences, so that only seventeen are configurations which are repeated.

All one hundred and one seams comprise part, or parts, of the whole of types 6E, 6F, 6K, 6L, 6M, 6P and 6Z (if the four ply increasing and decreasing profiles be condensed to three ply ones). These seven configurations themselves have common elements:-

6E:	4B + 2A	
6F:	4B + 2B	
6K:		2A + 4B
6L:		2A repeated
6M:		2A + 4D
6P:	4D + 2A	
6Z:	2B + 4H	

Types 6M, 6P, 6Z, 4D and 4H occur only once each, so that the remaining 95% of the seams could be considered to be composed of combinations and/or repetitions of the types 2A, 2B and 4B. Types 2A, 2B and 4B are defined as basic sequences of coal seam formation.

As so many seams are formed from the basic sequences, it suggests that basic sequence formation is not dependent on, or controlled by outside random influences, such as changes in sea level, but that the swamp environment itself must control the production of these forms. The seams which may have been affected by outside influences are those 5% of seams which have irregular or unrepeated profiles, where the natural peat sequence was disrupted.

TABLE 7.1.

Ratios of changes in microlithotype contents of adjacent plies for the Tivoli, Blackstone, Greta, Tomago, Moura and Nipan type seam sequences

Type Sequence	Plies	Vitrite + Clarite	Inter-mediates	Durite	Fusite
Tivoli	2/1	0.8	1.3	1.5	1.8
Blackstone	2/1	0.8	1.4	1.8	1.8
Greta	2/1	0.7	1.6	2.0	1.6
Tomago	4/3	0.7	1.6	2.7	1.7
Moura	2/1	0.8	1.4	4.0	1.5
Nipan	3/2	0.8	1.8	1.0	2.1
Tivoli	3/2	0.7	0.9	1.8	1.6
Blackstone	3/2	0.9	1.3	1.7	1.3
Greta	3/2	0.5	1.0	8.5	1.8
Tomago	5/4	0.4	0.6	4.0	1.2
Moura	3/2	0.6	1.2	6.0	1.6
Nipan	4/3	0.6	1.0	5.0	1.4
Tivoli	4/3	1.5	0.5	0.5	0.5
Blackstone	4/3	1.3	0.6	0.5	0.7
Greta	4/3	2.3	0.8	0.4	0.6
Tomago	6/5	3.6	0.8	0.1	0.7
Moura	4/3	1.6	0.9	0.3	0.7
Nipan	5/4	1.6	1.1	0.3	0.7

TABLE 7.2

Ratios of changes in microlithotype contents of adjacent plies in the Baralaba and Moura type seam sequences*

Seam	Plies	Vitrite + Clarite	Inter-mediates	Durite	Fusite
Baralaba β	β_2/β_1	0.7	1.4	8.0	1.6
Moura	3/2	0.6	1.2	6.0	1.8
Baralaba β	β_3/β_2	1.3	0.9	0.5	0.9
Moura	4/3	1.6	0.9	0.3	0.7
Baralaba β	β_4/β_3	0.7	1.1	3.0	1.3
Moura	5/4	0.7	0.9	5.0	1.3
Baralaba β	β_5/β_4	1.9	0.7	0.1	0.4
Moura	6/5	1.1	1.2	0.6	0.9

* These ratios are grouped in what are considered to be corresponding plies between the two sequences. For example, β_1 and β_2 are the two lowermost plies of the Baralaba β-type sequence, the vitrite-plus-clarite content of ply β_2 being 0.7 that of ply β_1.

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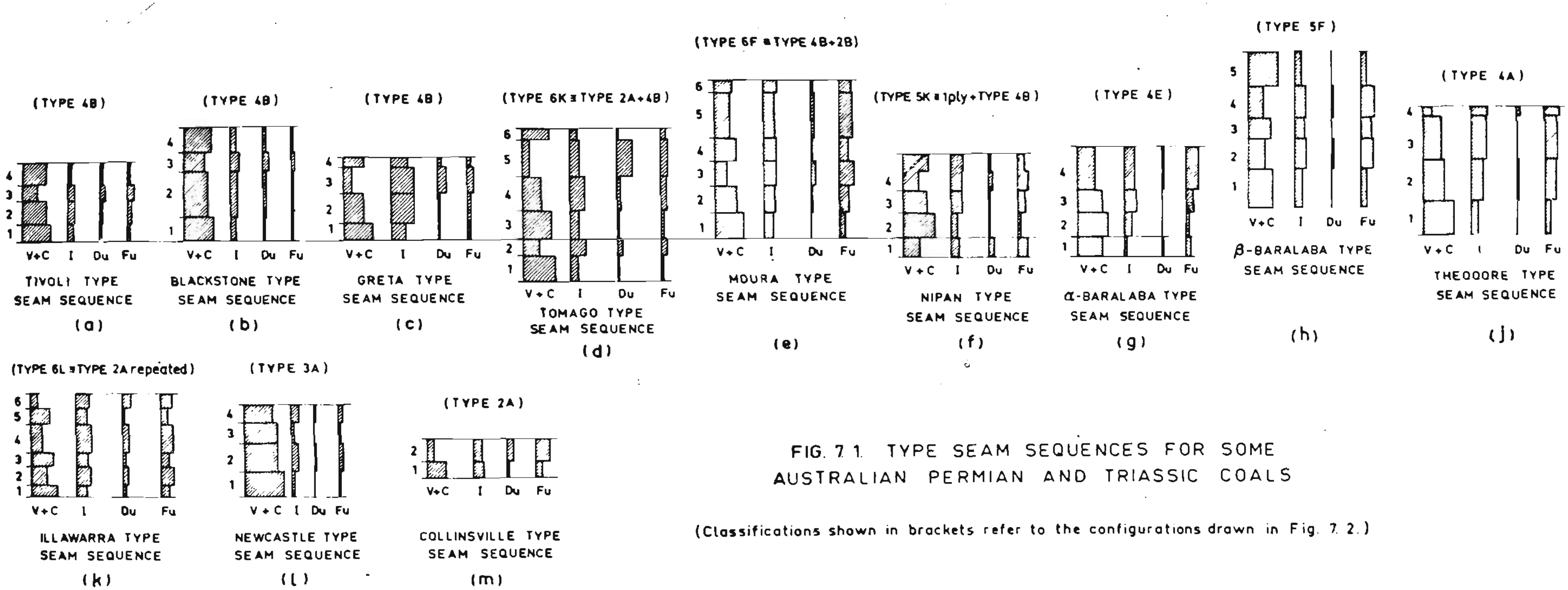

FIG. 7.1. TYPE SEAM SEQUENCES FOR SOME AUSTRALIAN PERMIAN AND TRIASSIC COALS

(Classifications shown in brackets refer to the configurations drawn in Fig. 7.2.)

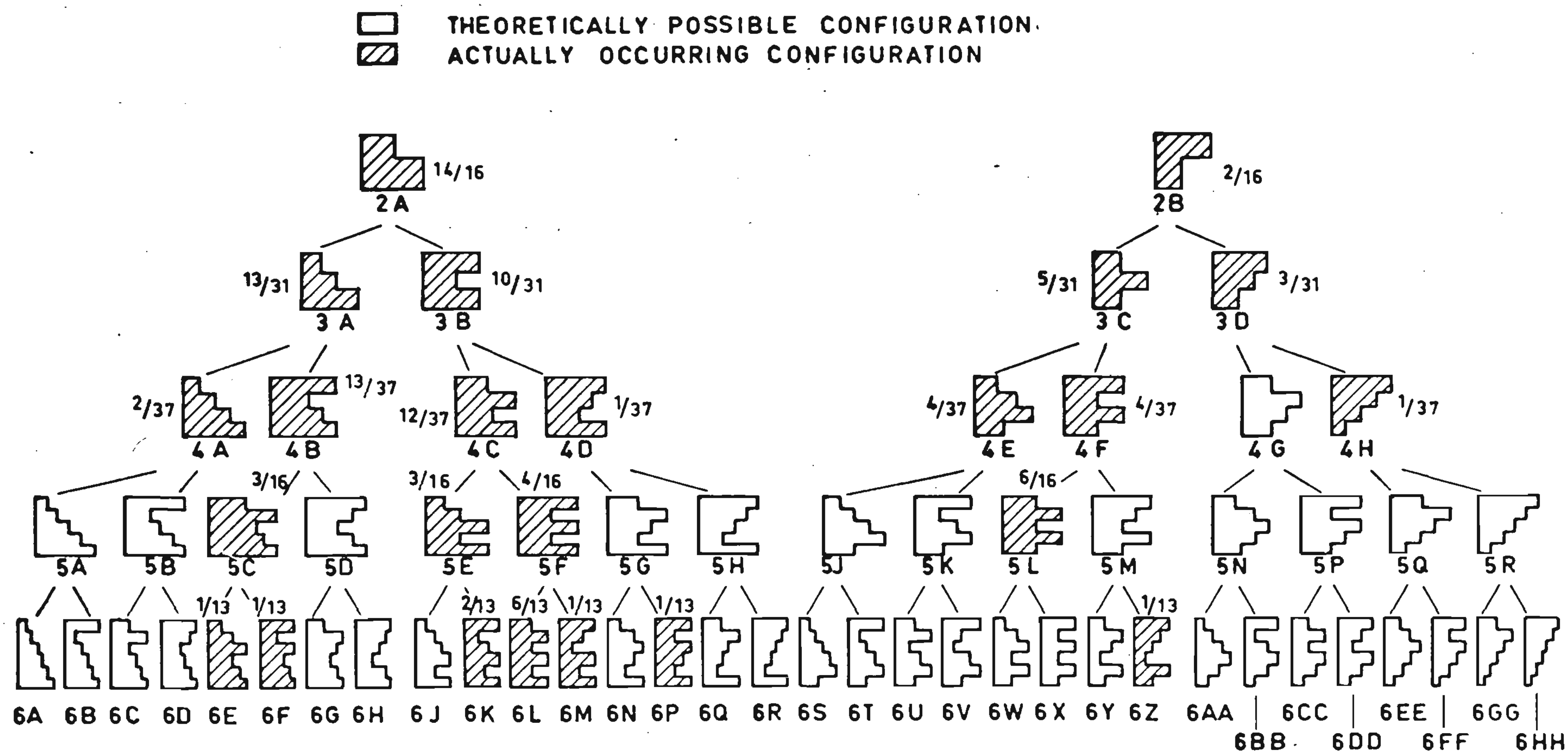

FIG.7.2.-SCHEMATIC REPRESENTATION OF ALL THE POSSIBLE WAYS IN WHICH THE VITRITE PLUS CLARITE CONTENTS OF SEAMS WITH FROM 2 TO 6 PLIES MAY VARY

8. STATISTICAL EVALUATION OF THE DISTRIBUTION OF TYPES OF PROFILES OCCURRING IN COAL SEAMS

(a) Introduction

Standard petrographic profiles have now been compiled for most of the economic seams in eastern Australia of Permian and Triassic age. Similarities in the vertical variations of the component microlithotypes of the seams have been shown amongst the standard profiles and the type seam sequences drawn from them. An attempt must now be made to discover whether these similarities are fortuitous or whether they indicate that the majority of the seams developed under ordered conditions. Smith (1962) found for the Carboniferous coals from the Yorkshire Coalfields that "The assemblages" (of miospores) "examined by the author from suites of samples from coal seams show not only that the different horizons within a seam have different dominant species but also that there is a regular pattern in the sequence of changes".

(b) Method

Figs. 8.1, 8.2, 8.3 and 8.4 show all the theoretical configurations which could be found in seams with from two to six plies for the microlithotype constituents vitrite plus clarite, intermediates, durite and fusite respectively.

If it is assumed that the changes in the environment of deposition of coal seams were purely random, each of the configurations in the above figures represents an equally likely event. It is however possible for a preponderance of one type over another to have occurred by chance alone, and the probability of this happening must be assessed in order to determine the significance of the distribution of the configurations.

An arbitrary level of the probability of a particular distribution of profiles occurring by chance must be selected, so that if the probability found were below that level, the distribution could be considered unlikely to have occurred by chance alone. For these coal seam profiles the level is taken to be 0.01; i.e. if the probability of a distribution occurring is less than one chance in one hundred, it is assumed unlikely to have occurred by chance alone.

To determine this probability the "Chi Square Test" was applied to the results found for the 2-ply, 3-ply and 4-ply configurations for each of the microlithotypes. There are insufficient samples in the 5- and 6-ply types to provide significant results. The observed and expected frequencies of occurrence of the profiles for the microlithotypes vitrite plus clarite, intermediates, durite and fusite are shown in Tables 8.1, 8.2, 8.3 and 8.4 respectively.

The values of "Chi Squared" and the probabilities derived from them are shown in Table 8.5. Most distributions (nine out of twelve) are found unlikely to have occurred by chance alone. The 2-ply distributions of the intermediates and fusite, and the 3-ply distribution of the vitrite plus clarite types could be due to chance alone, but all other distributions have probabilities of occurrence less than one in one hundred, so by previous definition, they are not due to chance. That is, the bulk of the results suggest that controlled conditions existed during the deposition of the majority of the seams.

(c) Inferences (see also section 9)

The four microlithotypes are interdependent because of the closed nature of the data, i.e. the vitrite plus clarite content of a seam varies inversely as the intermediates, durite and fusite contents. Therefore discussion of results is confined to the vitrite plus clarite profiles.

Most seams commenced with the accumulation of (relatively) vitrite-rich coal and became poorer in vitrite. These seams then followed three main lines of development, as indicated by the types of profiles outlined in Fig. 8.1. There is no prominent line of development of seams which commenced with the accumulation of (relatively) vitrite-poor coal and became richer in vitrite. The three lines of development strongly favoured by the coals are the series:-

2A	2A	2A	These are similar to the dominant sequences found using the Markov model (see section 4)
3A	3B	3B	
4B	4C	4C	
5C	5E	5F	

The only profile developed to any extent by coals starting with vitrite-poor coal is 5L, which is an alternating profile; after the initial conditions of deposition, this alternating sequence was presumably subjected to the same controls as the alternating sequence commencing with vitrite-rich coal (2A, 3B, 4C, 5F), so may be considered in conjunction with it. Such a sequence may be also simply an expression of coal deposition on an irregular surface, i.e. an undulating surface on which more vitrite-rich coals were deposited in the less oxidizing zones or areas structurally negative and more inertinite-rich coals in the structurally positive areas (Cook, 1969). In this way the one seam could provide examples of the two sequences.

This alternating sequence is statistically meaningless (Johnson and Cook, 1971), and does not necessarily imply cyclic sedimentation. However it has some geological significance in that it represents changes in depositional conditions. The other two sequences contain a third category of coal brightness and are therefore non-trivial sequences, in that they can show a preference between two choices when changing from one coal type to another. If preference is shown in this choice, some sort of controlled conditions are indicated.

There are sixteen possible series for the development of a five-ply seam, but the majority of the Permian and Triassic coals studied belong to only three of these, giving further indication of controlled conditions and as previously shown taken as a whole the sequences possess distinct Markovian properties.

(d) Type of control (see also section 9)

If most of the seams were deposited under ordered conditions which produced a limited number of variations in their petrographic profiles, it is logical that an internal controlling factor, or factors, must have been an integral part of the coal forming swamp. The variations in coal type cannot solely be attributed simply to such extraneous and independent events as isostatic and eustatic movements. For the British Carboniferous coals, Smith (1962) found that "Although fluctuating water levels are considered to be a major factor in determining the occurrence of the Incursion phase, they are not thought to be the primary cause of the sequence of phases, beginning with the Lycospore and terminating with the Densospore phase, but they may have a secondary influence....". That the control was an integral part of the coal-forming environment is supported by his statement; "The raised bogs of temperate climates have been studied in detail by plant ecologists and their development is known to be the result of a succession of vegetation cycles. The changes in the vegetation and the peat type are largely due to the control of the edaphic conditions by the plants themselves, although the rate of peat formation depends on the climate."

TABLE 8.1.

Frequencies for vitrite plus clarite

	Type	f(observed)	f(expected)
2 plies			
	2A	14	8
	2B	2	8
3 plies			
	3A	13	7.75
	3B	10	7.75
	3C	5	7.75
	3D	3	7.75
4 plies			
	4A	2	4.625
	4B	13	4.625
	4C	12	4.625
	4D	1	4.625
	4E	4	4.625
	4F	4	4.625
	4G	0	4.625
	4H	1	4.625

TABLE 8.2.

Frequencies for intermediates

	Type	f(observed)	f(expected)
2 plies			
	2A	7	10.5
	2B	14	10.5
3 plies			
	3A	3	9.5
	3B	6	9.5
	3C	21	9.5
	3D	8	9.5
4 plies			
	4A	1	4.25
	4B	1	4.25
	4C	10	4.25
	4D	0	4.25
	4E	3	4.25
	4F	8	4.25
	4G	8	4.25
	4H	3	4.25

TABLE 8.3.

Frequencies for durite

	Type	f(observed)	f(expected)
2 plies			
	2A	5	12.5
	2B	20	12.5
3 plies			
	3A	1	7.5
	3B	10	7.5
	3C	14	7.5
	3D	5	7.5
4 plies			
	4A	0	3.625
	4B	2	3.625
	4C	4	3.625
	4D	4	3.625
	4E	1	3.625
	4F	12	3.625
	4G	4	3.625
	4H	2	3.625

TABLE 8.4.

Frequencies for fusite

	Type	f(observed)	f(expected)
2 plies			
	2A	7	11
	2B	15	11
3 plies			
	3A	2	7.25
	3B	3	7.25
	3C	14	7.25
	3D	10	7.25
4 plies			
	4A	0	4.5
	4B	0	4.5
	4C	5	4.5
	4D	4	4.5
	4E	3	4.5
	4F	12	4.5
	4G	9	4.5
	4H	3	4.5

TABLE 8.5.

Values for "Chi Squared" and list of probabilities that values obtained are due to chance alone

Type	Degrees of Freedom	Chi Squared	Confidence level
Vitrite plus Clarite			
2-Ply	1	9	$P < 0.01$
3-Ply	3	8.097	$P < 0.05$*
4-Ply	7	38.89	$P < 0.01$
Intermediates			
2-Ply	1	2.33	$P < 0.20$*
3-Ply	3	19.89	$P < 0.01$
4-Ply	7	24.35	$P < 0.01$
Durite			
2-Ply	1	9	$P < 0.01$
3-Ply	3	12.93	$P < 0.01$
4-Ply	7	26.45	$P < 0.01$
Fusite			
2-Ply	1	2.9	$P < 0.10$*
3-Ply	3	13.62	$P < 0.01$
4-Ply	7	27.11	$P < 0.01$

* Chance of this distribution occurring is more than one in one hundred, i.e. may be due to chance alone for the purposes of this test.

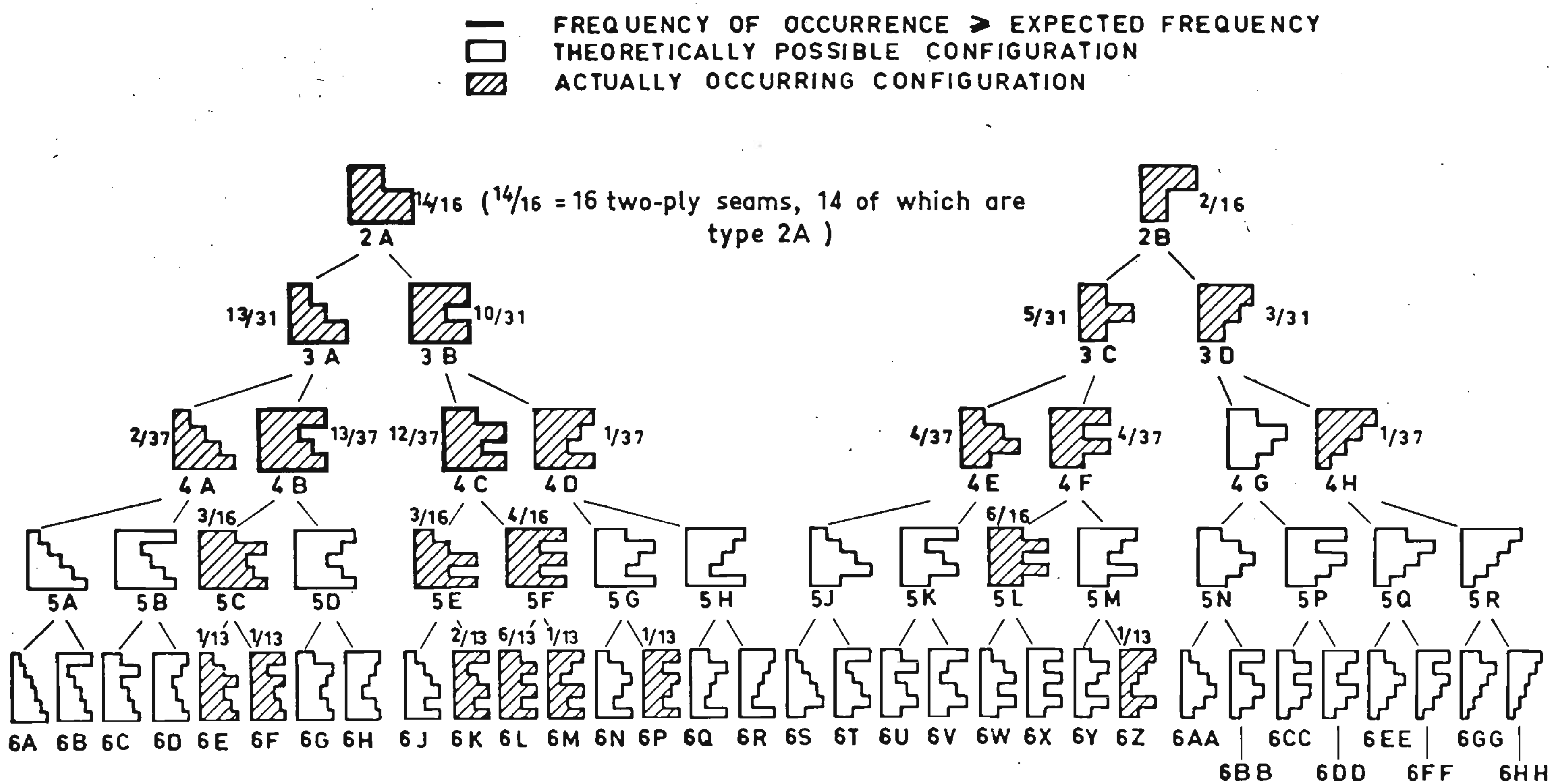

FIG.8.1.-SCHEMATIC REPRESENTATION OF ALL THE POSSIBLE WAYS IN WHICH THE VITRITE PLUS CLARITE CONTENTS OF SEAMS WITH FROM 2 TO 6 PLIES MAY VARY

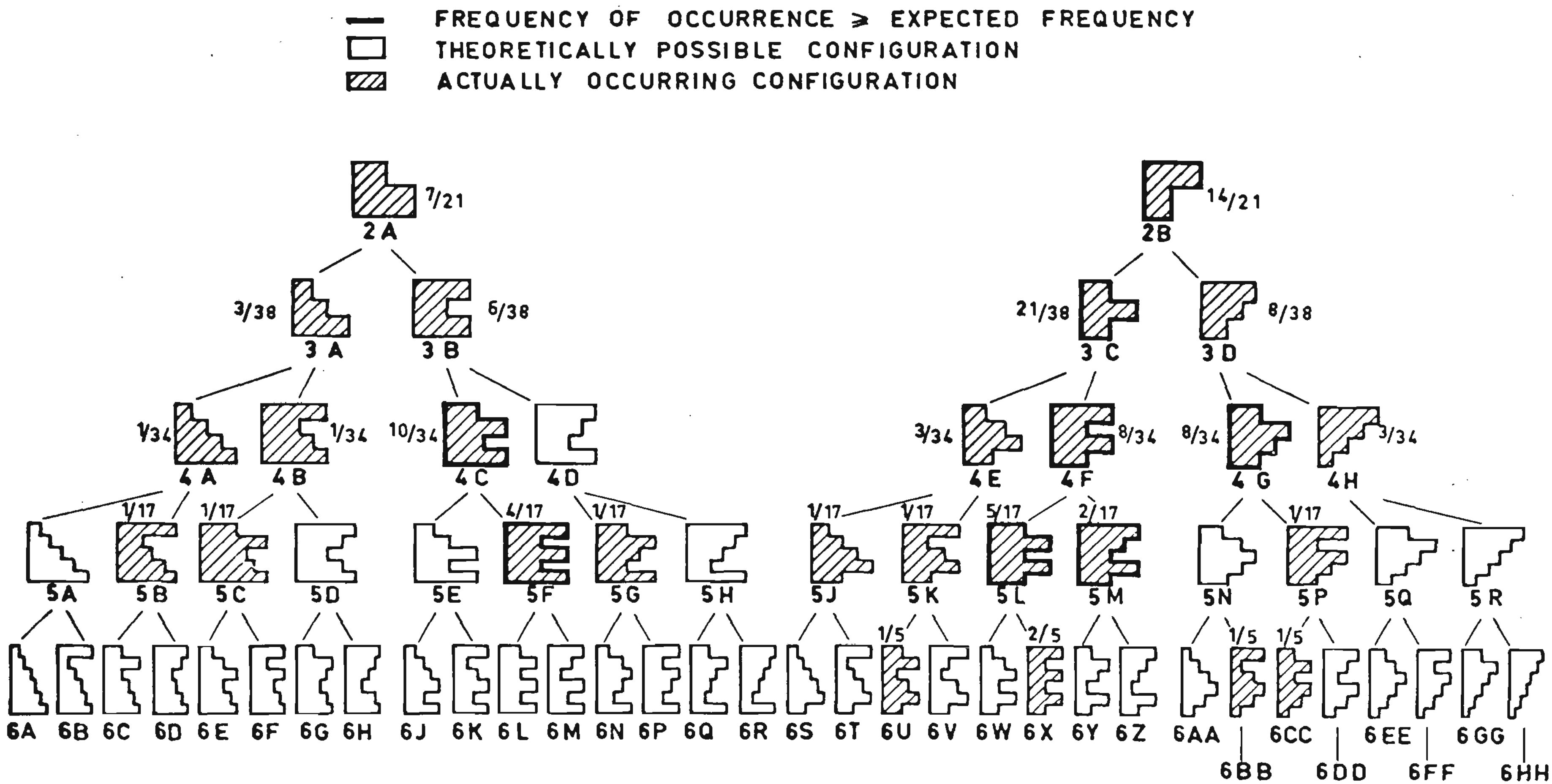

FIG.8.2.-SCHEMATIC REPRESENTATION OF ALL THE POSSIBLE WAYS IN WHICH THE INTERMEDIATES CONTENTS OF SEAMS WITH FROM 2 TO 6 PLIES MAY VARY

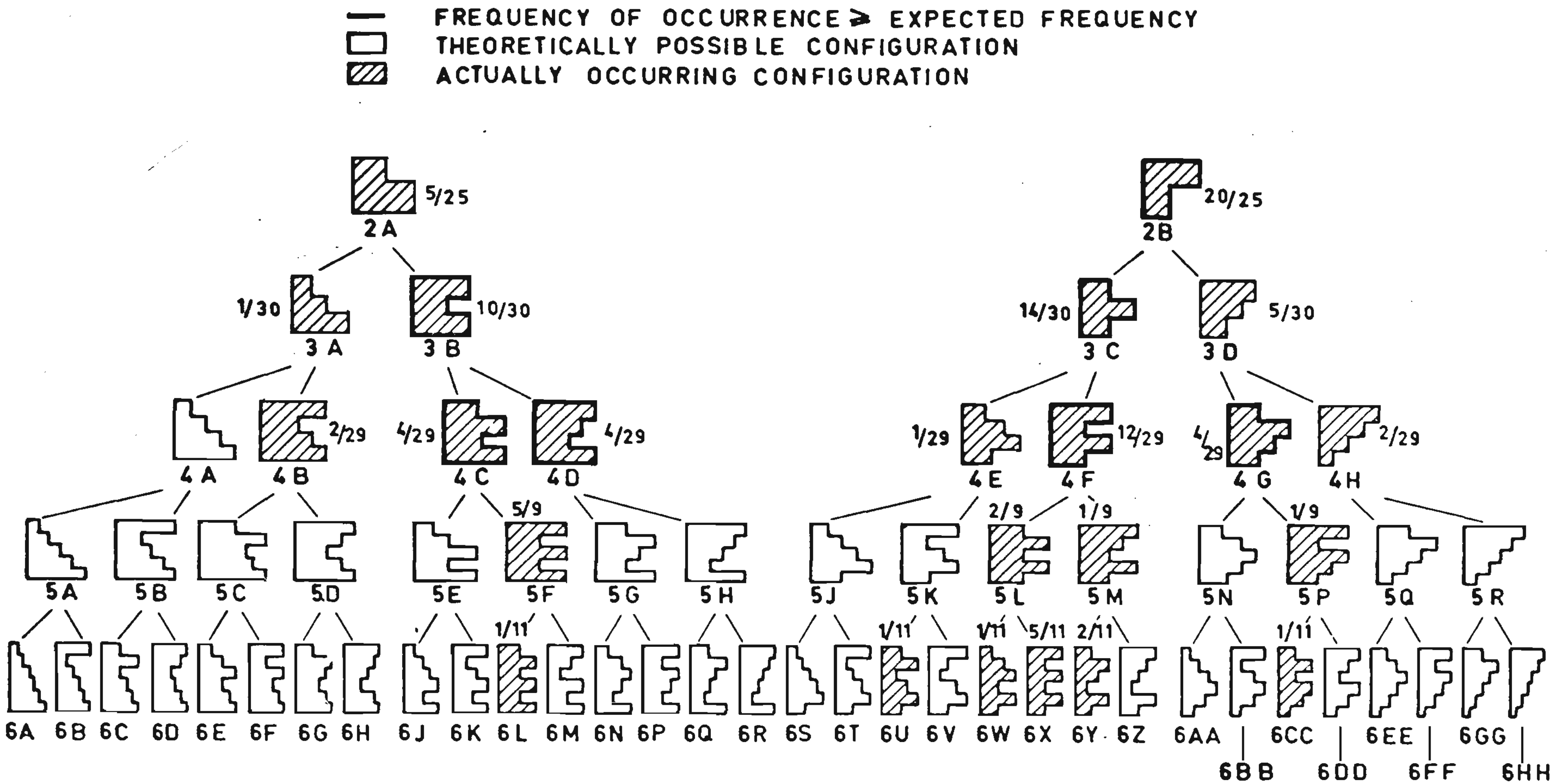

FIG. 8.3. - SCHEMATIC REPRESENTATION OF ALL THE POSSIBLE WAYS IN WHICH THE DURITE CONTENTS OF SEAMS WITH FROM 2 TO 6 PLIES MAY VARY.

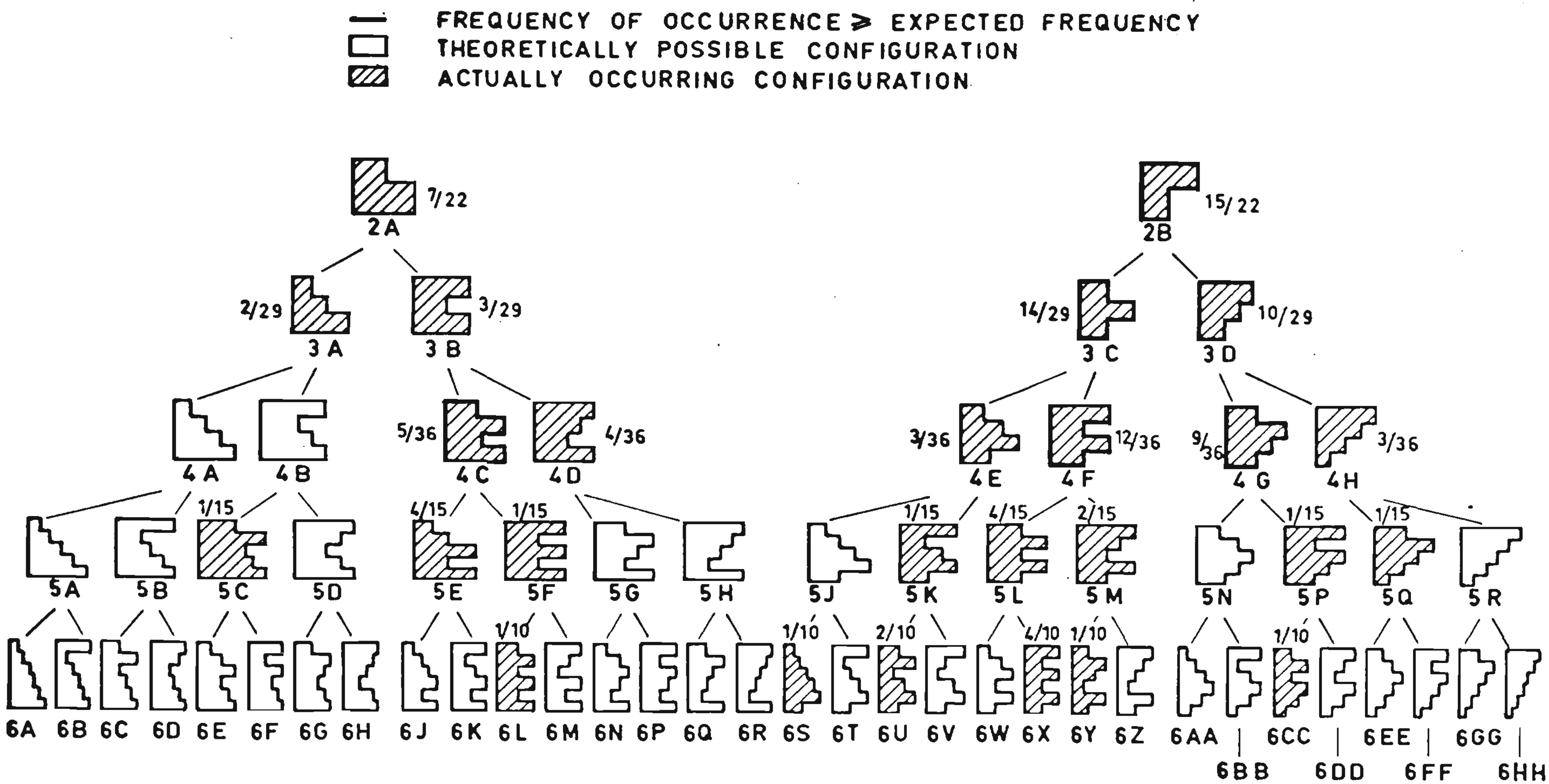

FIG.8.4.-SCHEMATIC REPRESENTATION OF ALL THE POSSIBLE WAYS IN WHICH THE FUSITE CONTENTS OF SEAMS WITH FROM 2 TO 6 PLIES MAY VARY.

9. DISCUSSION OF RESULTS AND THEIR IMPLICATIONS WITH RESPECT TO THE ECOLOGICAL CONDITIONS DURING COAL SEAM FORMATION

(a) Summary of results

The majority of the seams examined have been found to have Markovian properties, i.e. the state (vitrite plus clarite %) of any particular subsection is dependent on the state of the subsection immediately preceding it. When the coals are collected into large groups on the basis of stratigraphic affinity, the cyclic sequences found for the groups fall into four categories: (a) progressive upward decrease in the vitrite plus clarite content of the coal (Figs. 4.3 and 4.4; (b) progressive upward increase in the vitrite plus clarite content of the coal (Fig. 4.5); (c) upward decrease in the vitrite plus clarite content of the coal followed by a ply richer in vitrite plus clarite (Fig. 4.6) and (d) an alternation of vitrite plus clarite-rich, vitrite plus clarite-poor plies (Fig. 4.7).

The test for Markovian properties is only significant when applied to groups of seams and may be influenced by the non-stationary properties of some profiles so that another method had to be used to look for indications of a common control during deposition at the individual seam level. This has been done by dividing each seam into characteristic plies, which are macroscopically recognizable layers of coal representing different and distinctive depositional environments of long-standing duration and lateral persistence. Using these characteristic plies, first standard profiles of each seam have been compiled, and then seam profiles which are typical of more than half of the seams as grouped into coal measures. Marked similarities have been found between these type seam sequences, thus again indicating that the majority of seams have been influenced in their development by a common factor, or factors.

To test this assumption further the distribution of the types of the individual seam profiles found has been analysed for randomness, by comparison with theoretically possible profiles. Results of this test indicate that the distribution found for the seams is unlikely to have occurred by chance. The most favoured lines of development were those which included profiles the same as those of (c) and (d) of the Markovian cycles.

Accepting the initial limitation on the petrographic data - that the seams have been divided subjectively - all investigations of their patterns of formation strongly suggest that the majority of seams formed under controlled conditions.

(b) Discussion of results

For Markov chain analyses the seams have been grouped in accordance with stratigraphic affinities and for the Baralaba Coal Measures a decreasing profile is evolved; for the Illawarra, Lithgow and Newcastle (Moon Island Beach Sub-Group) first preferences give alternating sequences; **for** second preferences increasing and basic sequence profiles are found; for the Ipswich Coal Measures both basic and alternating sequences are found. These are not all in accord with the typical profiles found by the characteristic plies method. A possible explanation for this disparity is that the Markovian profiles have been obtained from subsections, whilst the type seam sequences have been compiled from characteristic plies, which are usually combinations of subsections. The Markovian and typical profiles may therefore represent development in the seams on two slightly different scales. In some instances the two types of profile are in agreement. This may indicate either that these trends are so strongly developed that the size of the initial subdivision is not critical; or that often individual subsections made up characteristic plies. Both methods indicate that the sequences are non-random in character.

Coal measures which have similar type seam sequences group together in some instances rather dissimilar sequences as far as the clastics in the succession are concerned. From Fig. 7.1, it appears that (a) the Tivoli, Blackstone, Greta, Tomago, Moura, Nipan and α- Baralaba type seam sequences are similar; (b) the β- Baralaba, Collinsville and Illawarra sequences; and (c) the Theodore and Newcastle sequences are similar.

In the Tivoli Formation sandstones are common, whilst shales are more so in the Blackstone Formation. Tomago sediments tend to be more fine-grained than Greta clastics, whilst the non-coal sediments of the Baralaba Coal Measures are predominantly sandstones. In this large grouping there is heterogeneity of associated clastics, with either shales or sandstones predominating in the various successions.

The principal clastics in the Baralaba, Collinsville and Illawarra Coal Measures are sandstones. The Theodore coals belong to the Baralaba Coal Measures where sandstones predominate; in the Newcastle Coal Measures conglomerates are an important element of the succession.

(c) Implications of results with respect to ecological conditions

Factors which have been used to explain the changes in coal type in seams are: (i) fluctuating water level in the swamp, (ii) variable oxidising potential of the water, (iii) variations in the type of vegetation, (iv) changing climate, (v) rate of subsidence and accumulation balance (Diessel, 1970; Sloss, 1962) and (vi) variations in edaphic conditions. All of these factors must operate during the deposition of a seam and will determine the type of coal deposited. The point of controversy is whether there is a major influence operating throughout the accumulation of the sediment, and if so, which of the above factors it is. Qualifications can immediately be placed on some or all of the factors by considering the results found in this and other studies.

Petrological and palynological studies on Carboniferous coals, petrological and statistical studies on Permian and Triassic coals, and botanical studies on recent peat bogs have all led to the conclusion that a primary control of peat development with respect to changes in peat type, comes from within the swamp environment itself.

The factors which are obviously external to the swamp system are the climate and rate of subsidence of the main basin area. Another which may be externally controlled is water level.

Therefore, climate and rate of subsidence cannot have been the major factors controlling the sequence of depositions of the seams studied. It is nevertheless considered that all the factors are interdependent, so that climate does exert some influence, and the rate of subsidence must lie within certain limits for coal to accumulate at all.

If changes in water level in the swamps are to be the major factor in producing the sequence of coal types, they may not be due to fluctuations in sea level (as is often stated), because such external and independent movements cannot logically be assumed to have occurred in a regular pattern to fit in with the formation of so many different coal seams. If sea level fluctuations are discounted, changes in the water level must be dependent on other factors, such as supply (external), drainage and evaporation. The oxidising potential of the water is controlled by the depth and movement of the water, so it is not the major factor.

Accumulation balance is dependent on (1) subsidence, (2) rate of accumulation of (a) inorganic clastics and (b) peat, and (3) rate of oxidation. It is not the major factor controlling the sequence of coal type variations because it contains externally controlled factors. It is envisaged that (1) and (2(a)) may interrupt, initiate or terminate peat formation, but that the control of the sequence of changes is by (2(b)) and (3).

This leaves the type of vegetation and the edaphic conditions as possible major factors. In this case it must be decided which one is controlled by the other, remembering that it is the control of the changes in coal type after a peat forming environment has been established, For the establishment of this peat-forming environment, there must be a critical point in the depositional area at which organic material takes over from inorganic sediments. This will be dependent on a suitable rate of subsidence, a favourable climate and a certain depth of water. It has been shown that most seams commence with bright coal, which is here considered to represent the growth of large trees in the maximum depth of water to occur in the swamp which permits vegetal growth. Under these circumstances it is the edaphic conditions which control the type of initial vegetation. However, it has been found that large thicknesses of accumulated peat can change the edaphic conditions to the extent that the forest vegetation can no longer be supported and this in turn produces a change in vegetation to smaller trees and shrubs. It would seem that these two factors are mutually dependent, but on balance, as the vegetation produces the edaphic conditions, the type of vegetation must be considered as the major controlling factor. That is, once initial favourable conditions have been established, the plants themselves take control of their environment, and changes in coal type are produced as a result of the natural succession of plant types. Climate and vegetation probably control the type of peat which accumulatesbut are unlikely to have produced the consistent set of sequential changes found in the present study.

The most common types of profile found suggest a history typically commencing with forest vegetation, which, while accumulating, changes the edaphic conditions (Duff, 1967a) and also lowers the depth of water or water content as the peat deposit rises. Thus the change to sparse vegetation is produced by the edaphic conditions, but also to an extent by the water level, which is now sufficiently shallow to permit the growth of smaller plants. Not only is the type of organic matter changed, which in itself should give rise to coal type variations, but the oxidising potential of the water is altered, so that the different starting material will be decomposed to a different extent. The type of vegetation changes progressively in the direction of smaller and sparser vegetation, towards grasses and reeds, lowering further the water level due to accumulation, and permitting greater degradation of the organic material, with possibly eventual exposure to the air (Smith, 1962). This sequence of events is represented in the resultant sediment by a change from vitrinite-rich to inertinite-rich coal.

Many seams show this cycle only once on a large scale, terminating with more vitrinite-rich coal as the water deepens due to accelerated subsidence which finally ends peat deposition. However, even more often this sequence from vitrinite-rich (bright) to inertinite-rich (dull) coal is repeated. Frequently the dull coal is followed by a dirt band, indicating changed edaphic conditions of deepened water and new soil. When this dirt band is the roof of the seam, it is logical to explain it by accelerated subsidence; but when seam deposition continues on, another explanation would be preferable.

Such an explanation could be that, having reached an inertinite-rich phase, where vegetation is meagre and degradation is extreme, the rate of peat accumulation must drop significantly, so that assuming a constant subsidence rate, the situation arises where the water deepens again and either the existing vegetation is killed off so that inorganic deposition takes place (dirt band), which can then support forest vegetation (bright coal): or, the grasses and reeds are gradually replaced by the shrubs and bushes as the water deepens, producing brighter coal than before, but not so bright as the bright coal of the first cycle. This explains why even though cycles are repeated they tend to become duller overall towards the top of a seam (viz. the cyclicity is non-stationary).

The petrological and statistical studies have been instrumental in adding to the knowledge of the processes operating during the formation of coal seams by showing the existence of sequential dependence of coal types, preferred sequential development, and that internal factors are dominant in controlling coal type variations.

10. COMPARISON OF AUSTRALIAN PERMIAN AND TRIASSIC COALS WITH EUROPEAN AND NORTH AMERICAN COALS

(a) Introduction

With so many petrographic profiles of Australian seams available, comparison with a like number of seam profiles of European and North American coals could provide comprehensive and statistically meaningful results. However, very few petrographic profiles are available from the literature, so the Australian coals can only be compared with a small number of seams from the Northern Hemisphere.

The Permian and Triassic seams from Australia have proved to be very similar to one another, to the extent that it seems unlikely that age and geographic location of a deposit, at least, have any bearing on the type of coal produced in a swamp. This idea would be further supported if coals from Europe and North America of Carboniferous age should prove to have petrographic profiles similar to those of the Australian coals. If it should be found that these Carboniferous coals have a limited number of profiles, especially ones similar to those formed from the Australian basic sequences, then it would appear that coal seams from any age or any locality were subjected to the same controls during accumulation, further supporting the premise that major control of conditions could lie within the swamps themselves. If these similarities were due to outside controls, then these controls must have been common to the majority of coal seams. It is logically less likely that the same external conditions were repeated whenever a coal seam was forming, than that the same internal conditions occurred.

(b) Comparison of petrographic profiles

In comparing the forms of Australian coals with those of European ones, the first gross similarity is that noted by Bell (1966), that the British Carboniferous coals tended to be bright at the base and duller at the top. This is true for the majority of Australian coals also.

The only detailed petrographic profiles of British coals available are those samples of the Barnsley, Thorncliffe and Swallowood seams from the Yorkshire Coalfield, with microlithotype analyses supplied by A.H.V. Smith of the National Coal Board of Great Britain (pers. comm These seams were analysed at 5, 2.5 and 1cm intervals respectively. After grouping into characteristic plies, as has been done for all the Australian coals, the Barnsley seam shows a simple alternating vitrite plus clarite profile (Fig. 10.1). The Thorncliffe seam is also simple alternating (Fig. 10.2), and the Swallowood seam has a complex alternating profile (Fig. 10.3). From descriptions given by Smith (1962), the seams he studied were either alternating or of Greta-like profiles. (Greta-like is equivalent to one of the basic sequences.)

(c) Use of petrographic profiles as an indicator of environment

Coals from Canada described as "paralic" by Hacquebard, Birmingham and Donaldson (1967) are the Harbour[1] seam from the Sydney Coalfield, the No. 5[1] seam from the

1 Carboniferous, Nova Scotia

St Rose-Chimney Corner Coalfield and the Wellington[2] seam from the Nanaimo Coalfield. The Harbour seam has a vitrite plus clarite petrographic profile similar to the Tomago type seam sequence, with the top ply missing (Fig. 10.4). The No. 5 seam has an alternating profile (Fig. 10.5), as does the Wellington seam (Fig. 10.6).

Three samples of "limnic" coals from Canada are shown in Figs. 10.7, 10.8 and 10.9. The No. 2 seam[1] from the Springhill Coalfield has a Greta-like profile, with the differences between each characteristic ply not very great, somewhat similar to the Blackstone type seam sequence. The Scott seam[1] from the Pictou Coalfield has a profile of similar form to the Nipan type seam sequence, although with lower vitrite plus clarite content, and the seam from the Telkwa Coalfield[2] has an alternating profile.

Thus two "paralic" seams have alternating profiles, one a Greta-like, or basic sequence, plus one ply: two "limnic" seams have basic sequence profiles, (one with an extra ply) and the third is alternating.

The Tracy seam from the Sydney Coalfield, presumably also paralic, has an alternating profile in the Broughton Mine, and a Moura type, or basic sequence plus two plies in Hiawatha Slope. The alternating profile is like the β-Baralaba, so could be an incomplete Moura sequence (bottom ply missing) (Fig. 10.10).

Although there are too few samples to obtain really meaningful results, the data of Hacquebard et al., taken in conjunction with their interpretations of environment could be taken to suggest

1 Carboniferous, Nova Scotia
2 Cretaceous, British Columbia

that a paralic environment, i.e. one influenced by changes in sea level, gives rise to coal seams with alternating profiles; whilst a limnic environment, or one not affected by sea level fluctuations, gives rise to the Greta-like basic sequence. That is, in a closed system of peat accumulation, the basic sequence is likely to develop, whereas an area where peat accumulation is interrupted by outside occurrences gives rise to alternating profiles.

If the Greta-like basic sequence were taken to be (on the basis of the data of Hacquebard et al.) characteristic of limnic basins, those Australian coals in which the sequence occurs are the majority of seams from the Greta, Tomago, Newcastle (lower), Baralaba and Ipswich Coal Measures. Those coals with alternating profiles, on the same argument representative of a paralic environment, are the majority of seams from the Collinsville, Illawarra and Newcastle (Moon Island Beach Sub-Group) Coal Measures.

These inferences from the work of Hacquebard et al. concerning environment, conflict with commonly held views of environment of the Australian sequences listed above. In particular, the Moon Island Beach Sub-Group, and to a lesser extent the Illawarra Coal Measures, seem to lack any indication of marine influence, and the Moon Island Beach sequence appears to fit most of the criteria for a limnic environment, although it may well have formed in the alluvial regime of an essentially paralic province.

Equally the Greta Coal Measures must be assessed as having close affinities to the paralic environment, being in all probability representative of a lower deltaic regime.

It is interesting therefore to compare the data on profiles with Swaine's data on boron content. Swaine (1962) has associated the boron content with the sedimentary environment for New South Wales Permian coals, with indications that "The Greta Coal Measures were influenced by marine conditions, the Tomago by brackish or intermittent marine conditions and the Illawarra by fresh water conditions. The values for the Newcastle Coal Measures indicate conditions somewhere between brackish and fresh water, but nearer the latter." The boron content for 90% of coal samples from Illawarra seams is 40 ppm or less; for Newcastle seams it is 50 ppm or less; for Tomago seams, 70 ppm or less; and for Greta coals it is 160 ppm or less.

Table 10.1 shows the boron content figures for Queensland Permian and Triassic coals and New South Wales Permian coals; the possible type of environment in which they formed from their most common type of petrographic profile; and the type of environment indicated by their boron contents. Nova Scotian coals from the Sydney Coalfield are also included.

Agreement between the types of environment indicated by interpreting petrographic profiles on the basis of the work of Hacquebard et al., and by interpreting boron content, is poor. As the Sydney (Nova Scotia) Coalfield coals have one of the lowest boron contents (indicating fresh water), but are cited by Hacquebard et al. as examples of paralic seams, other factors must be involved.

In fact, the Sydney Coalfield has no known marine sediments, but is described as paralic on evidence other than that of marine incursions. The only paralic seam for which there is evidence of marine influence is the Wellington seam in the Nanaimo Group.

Clearly many more Carboniferous seam profiles are needed before any detailed and significant comparisons can be made. However, the petrographic profiles of the seams available from Yorkshire and Nova Scotia are similar in form to Australian seams, and, moreover, contain the basic sequences found for Australian coals.

The data so far suggest that for Australian coal seams the profiles cannot be used to distinguish paralic and limnic environments.

TABLE 10.1

Comparison of environment deduced using (a) Hacquebard (b) Boron content

Coal measures	Boron content ppm	Environment from petrographic profiles (a)	Environment from boron content (b)
Greta	160	limnic	marine infl.
Tomago	70	limnic	brackish
Newcastle	50	limnic-paralic	fresh water*
Baralaba	20	limnic	fresh water*
" :Moura	40	limnic	fresh water*
" :Nipan	25-80	limnic	brackish
" :Theodore	not available	limnic	-
Ipswich:Tivoli	not available	limnic	-
" :Blackstone	40	limnic	fresh water*
Collinsville	< 10	paralic	fresh water
Illawarra	40	paralic	fresh water
Callide	< 20	?	fresh water
Nova Scotian coals from Sydney Coalfield	6-25, 17 average (Hawley, 1955)	paralic (Hacquebard, 1967)	fresh water

* Agreement between environments indicated by petrographic profiles and boron content using Hacquebard et al.'s criteria.

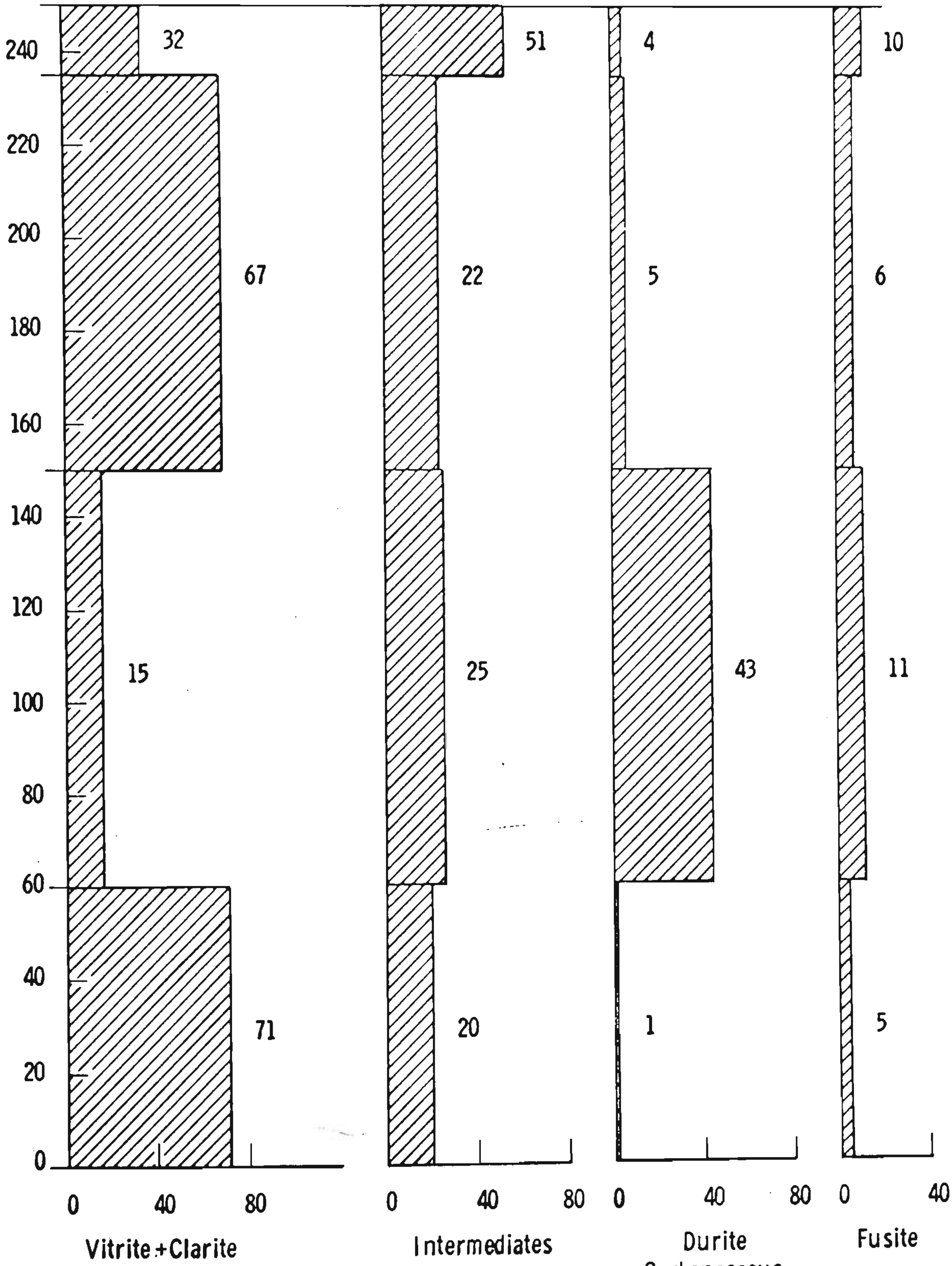

Fig. 10. 1. Barnsley Brodsworth 5's

(Analyses for every 5 cm supplied by A. H. V. Smith, National Coal Board U. K.)

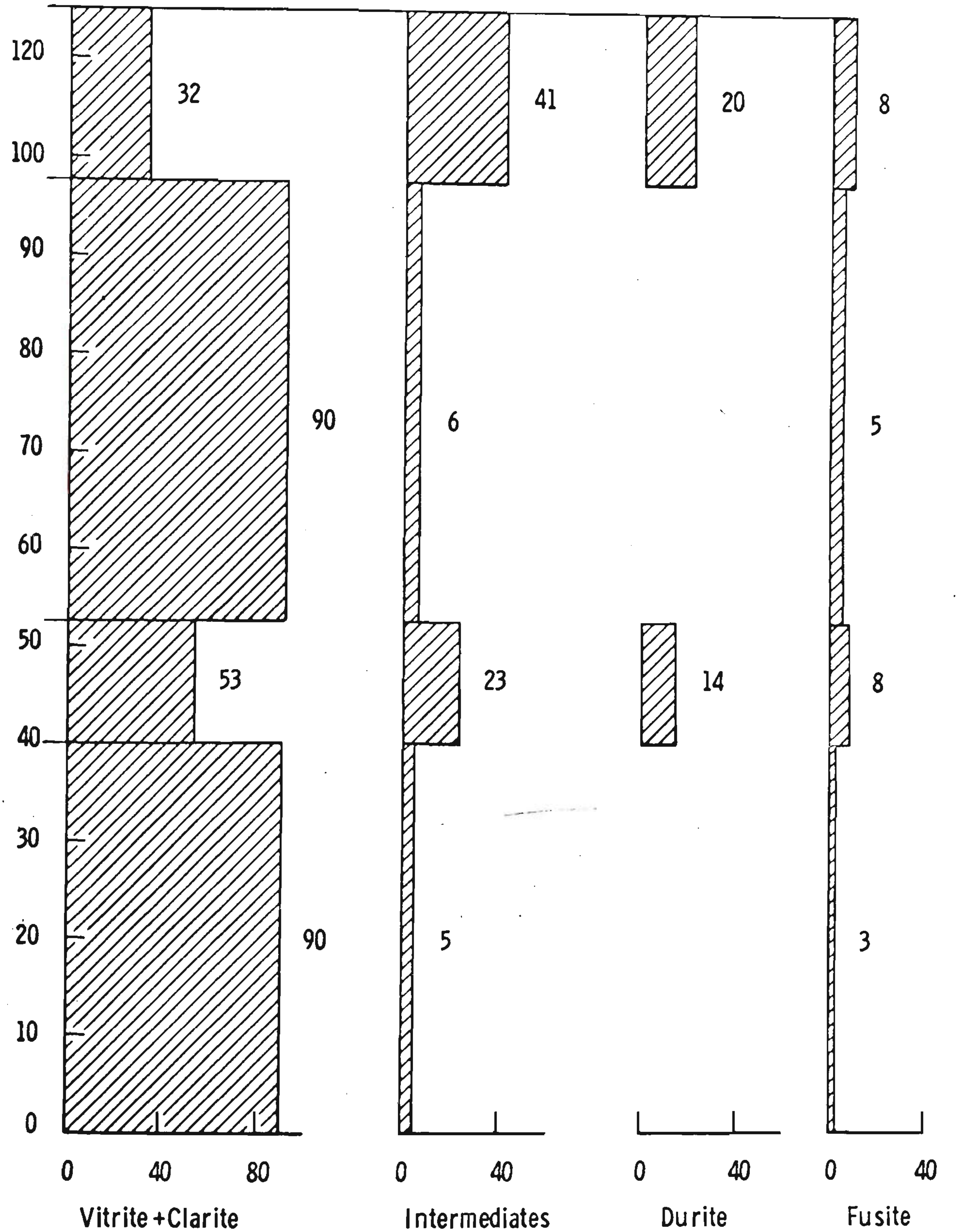

Fig. 10. 2. Thorncliffe Seam - Brodsworth 300's
(Analyses for every 2·5 cm supplied by A.H.V. Smith, National Coal Board U.K.)

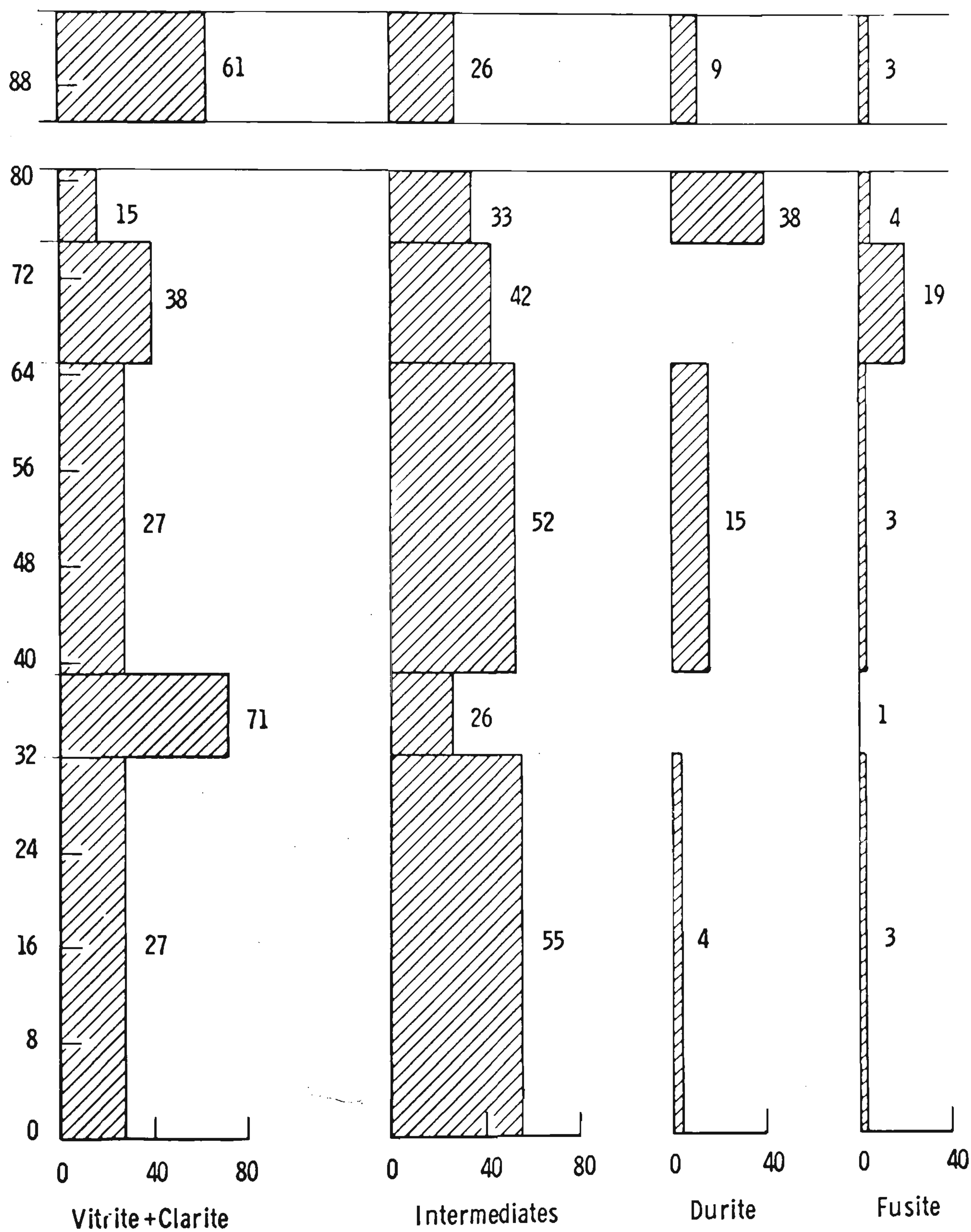

Fig. 10. 3. Swallowood Seam - Barrow

(Analyses for every 1 cm supplied by A.H.V. Smith, National Coal Board U. K.)

Reproduced from Hacquebard et al. 1967

Please see print copy for image

Fig. 10. 4. Sydney Coalfield - Harbour seam

Reproduced from Hacquebard et al. 1967

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Fig. 10. 5. St. Rose - Chimney Corner Coalfield - No. 5 seam

Reproduced from Hacquebard et al. 1967

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Fig. 10. 6. Nanaimo Coalfield - Wellington seam

Reproduced from Hacquebard et al. 1967

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Fig. 10. 7. Springhill Coalfield No. 2 seam

Reproduced from Hacquebard et al. 1967

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Fig. 10. 8. Pictou Coalfield Scott seam

Reproduced from Hacquebard et al. 1967

Fig. 10. 9. Telkwa Coalfield

Reproduced from Hacquebard, 1952

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Fig. 10 · 10

11. CONCLUSIONS

The petrographic analyses of over one hundred Australian coal seams of Permian and Triassic age have been used to indicate the ecological conditions prevailing during coal seam formation.

When seams are grouped into their respective coal measures (for statistically meaningful numbers), the transitions between their subsections are found to have Markovian properties, i.e. the state of any subsection is dependent on the state of the preceding subsection. In this case the "state" has been defined by the vitrite plus clarite content of the coal ("brightness"). The vitrite plus clarite contents of each subsection of the seams have been tested for Markovian properties, both including and excluding associated dirt bands. When dirt bands are included the most probable sequences found are more cyclic and more groups have the same sequences, indicating that the dirt bands could be an essential step in the patterns of formation. The presence of Markovian properties points definitely to the seams having accumulated under controlled conditions.

Coals have also been examined for sequences at the individual seam level by dividing them into characteristic plies, which represent different environments of long duration and lateral persistence. This ensures that the large scale changes in a seam can be correlated from one sampling area to the next, and that these changes are not obscured by the finer detail of the subsections. A standard profile of each seam has been compiled from one or more samplings. When the seams are grouped into their coal measures, it is found for all but one of the measures that more than half of the standard profiles in each have similar petrographic sequences to one another. A profile typical of each of these coal measures has been compiled from the standard profiles.

Many of the type seam sequences are similar. This supports the previous findings from statistical tests, that the stages in a sequence are interdependent, and again indicates controlled conditions during the deposition of the seams. The type seam sequences could all be derived from combinations of the whole or parts of a very few basic sequences.

When the profiles of the microlithotype contents of all the seams are tested for randomness of distribution against theoretical configurations, the distributions are found unlikely to be due to chance. This further confirms the hypothesis that coal seams do not accumulate in an irregular manner. There are three prominent lines of development which the seams follow, which are similar to the sequences found from the Markov tests.

The purpose of all the experimental work has been to determine whether coal seams accumulate in a haphazard fashion, or if there is some order imposed on their deposition. The conclusion which may be drawn from the results is that there is order and that this order is manifested as a small number of distinctive patterns in most of these seams. It follows from this that the controls which bring about this order originate within the swamps themselves, as no external agent could be logically expected to vary in a definite sequence in step with the formation of all the coal seams.

There are several factors which must influence the development of a coal seam: (a) depth of water, (b) oxidising potential of the water, (c) climate, (d) rate of subsidence and accumulation balance, (e) type of vegetation and (f) edaphic conditions. One of these must be the major control of the changes in coal type. As the major control is internal, climate and rate of subsidence are automatically eliminated. Oxidising potential is dependent on depth of water, which is itself dependent on other internal factors if it is not to be controlled by external events. The accumulation balance is dependent on other factors, given by the equation

$$
\begin{aligned}
\text{accumulation balance} = {} & -f\ (\text{subsidence})[1] + f\ (\text{rate of accumulation of inorganic clastics})[2] \\
& + f\ (\text{rate of accumulation of peat})[3] \\
& - f\ (\text{rate of oxidation})[4]
\end{aligned}
$$

Term [1] determines whether peat will accumulate or not, rather than the sequence of changes in the peat. Terms [2], [3] and [4] have more direct bearing on the production of the ordered sequences of peat changes.

The type of vegetation and edaphic conditions are mutually dependent, but after the initiation of peat accumulation, the plants control the edaphic conditions, rather than the other way round.

The majority of coal seams have developed under controlled conditions; and the plants are the major control effecting changes in coal type.

Comparison of the profiles of the Australian coals with Carboniferous and Cretaceous seams from England and Canada indicates that the same types of profiles have developed in the Carboniferous and Cretaceous coals.

Petrographic profiles have been used as a means of seam correlation. This study shows that many profiles of Australian coal seams are similar, especially those of seams belonging to the same coal measures. Because of this it is not possible to effect reliable correlation by comparing single seams. This can only be done by comparing whole successions.

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APPENDIX: GENERAL GEOLOGY AND LOCATION OF SAMPLES

(a) New South Wales - Permian

All the New South Wales coals studied are from the Sydney Basin and are of Permian age. The following descriptions of the general geology and locations of the samples are from the Journal of the Geological Society of Australia, Volume 16, Part 1: The Geology of New South Wales (1969) (Packham: editor). Figures A.1 to A.8 are reproduced from this volume.

(page 311) "The Sydney Basin is a broad structural basin. It is bounded on the east by the coastline...but must extend eastwards under the continental shelf and perhaps part of the continental slope. The western boundary," (is) "an unconformity against folded and faulted lower and middle Palaeozoic rocks.. A structural boundary then swings eastward to embrace the southern side of the Goulburn River Valley to Sandy Hollow and the Hunter Valley from Murrundi to the coast..." (Fig. A.1).

(page 313) "The basin and its northern extension was essentially an area of Permian and Triassic sedimentation... The broad stratigraphic succession recognized within the basin proper is shown in" Table A.1.

"The most complete sequence of Permian rocks within the Sydney Basin is exposed in the Hunter Valley." (Fig. A.2) "The Permian rocks are developed in alternating marine and continental sequences... The terminology of the major rock units used in this volume" (Table A.2, columns 2 and 3) "follows that of Booker, but his nomenclature has been modified or extended as a result of the most recent geological studies..." (Booker, 1960).

(page 323) "David (1888) introduced the name <u>Greta Coal Measures</u> at Greta...

The Greta Coal Measures are widely distributed in the Hunter Valley, but their outcrop is poor and confined to a few areas...

The characteristic lithology of the measures in the vicinity of the Lochinvar Anticline is fine-grained conglomerate... Associated with the conglomerate are sandstone, siltstone, mudstone and shale. There are up to five seams in the sequence and plant fossils are common throughout." (Fig. A.3).

(page 328) "The Greta Coal Measures outcrop on the crest of the Muswellbrook Anticline and have been traced by Booker (1960) from a few kilometres north of Muswellbrook to Savoy Trig. Station, a distance of about 12 miles (20 km)..." (Fig. A.4)... The measures comprise freshwater sediments which differ from those in the lower Hunter area by the general decrease in grain size and the relative unimportance of conglomerates. Further differences are the increased thickness of coal within the measures and the development of a thick barren phase below the lowest coal seam which has not been encountered outside the Muswellbrook district..."

(page 334)..."The <u>Tomago Coal Measures</u> overlie the marine Maitland Group and are overlain by the Newcastle Coal Measures." (Fig. A.5). "They outcrop on the eastern flank of the Lochinvar Anticline, near

East Maitland, and dip gently in a general southeastward direction towards the coast...(Fig.A.2). South of the area of outcrop the measures disappear under Newcastle Coal Measures... On the western flank of the Lochinvar Anticline sediments equivalent in age to both Tomago and Newcastle Coal Measures outcrop; owing to difficulties in differentiation, the western beds have been grouped as the Singleton Coal Measures...

Tomago sediments...are characteristically more fine-grained than those of the Greta or Newcastle Coal Measures and consist mainly of shales, mudstone and sandstone with a number of coal seams and claystone horizons, some of which are of tuffaceous origin...".

(page 339) "The Newcastle Coal Measures...occur...southward from the lower reaches of the Hunter River at Newcastle and westward from the coast to the western side of the Sugarloaf Range." (Fig. A.2). "To the south, the upper coal seams of the Newcastle Coal Measures have been identified as far south as the southern shore of Tuggerah Lakes although the Measures generally extend to the south and west over almost the whole of the Sydney Basin, underlying rocks of the Triassic System." (Fig. A.6).

"In addition to coal and other carbonaceous material the sediments consist essentially of five rock types: conglomerate, sandstone, sandy shale and shaly sandstone, shale and tuff..."

(page 350) ..."Coal measures equivalent in age to both the Tomago and Newcastle Coal Measures occur on the western flank of the Lochinvar Anticline and extend in outcrop northwest up the Hunter and Goulburn Valleys. These beds have been named the <u>Singleton Coal Measures</u> (Robinson, 1963b)... (unpublished).

The Singleton Coal Measures...consist mainly of sandstones, mudstones, shales and conglomerates with numerous intercalated coal seams." (Fig. A.7).

(page 355) "The Permian sequence south and west of the Hunter Valley is incomplete... The 'upper' coal sequences (Tomago and Newcastle Coal Measures) have probable equivalents in the centre on the basin... but farther south and west the coal measures are thinner and appear to represent deposition in 'Newcastle' time only."

(page 370) "The <u>Illawarra Coal Measures</u> form the south eastern segment of the Sydney Basin." (Fig. A.1)... The full sequence of the coal measures is exposed near Wollongong..."

(page 372) "The stratigraphic sequence of the Illawarra Coal Measures is shown in" Table A.3 and Fig. A.8.

(page 376) "The principal rocks of the Illawarra Coal Measures are sandstone, shale, tuff, coal and associated carbonaceous sediments..."

(page 377) ..."Splitting and coalescence of coal seams, a characteristic of the Northern Coalfield, are uncommon and never on a major scale...".

(b) <u>Queensland - Permian and Triassic</u>

The general geology of the sediments associated with the Permian coals of Queensland has been described by D. King and P.W. Goscombe in "Coal Geology of the Bowen Basin" (Q. Govt. Min. J. Vol. LXIX, No. 805, Nov. 1968). Fig. A.9 is reproduced from this paper.

"The Permian sequence of the Bowen Basin has been grouped by earlier geologists into three broad stratigraphic sub-divisions: namely the Lower Bowen Volcanics and intercalated marine sediments of Lower Permian age, the Middle Bowen Beds comprising a sedimentary succession dated as Lower to Upper Permian...bymarine fossils, and the Upper Bowen Coal Measures featuring the characteristic Permian Glossopteris and Gangamopteris flora. Coal measures are known in both the Lower and Middle Bowen successions and comprise practically the full thickness of Upper Bowen deposits.

The Lower Permian Collinsville Coal Measures, in the middle part of the Middle Bowen succession, are important at the northern and western extremities of the Basin." (Fig. A.9).

"The Geology of the Collinsville Coal Measures" has been described in a paper by E.A. Webb and C.E. Crapp (1960). Fig. A.10 is reproduced from this paper. "The Collinsville Coal Measures consist mainly of arenaceous sediments but include eleven named coal seams... The Coal Measures are predominantly sandstones, with coal seams, siltstones, shales and conglomerates... The lowest, and generally the thickest, of the coal seams is the Blake, and the top seam is the Murray which, except in a few isolated areas where it is overlain by a thin shale bed, is overlain by the basal conglomerate of the Middle Bowen Marine Beds... The stratigraphic column for the Coal Measures is shown in " Fig. A.10.

(King and Goscombe, page 494)..."The Upper Bowen Coal Measure sequence, or Blackwater Group as it is now more formally known, constitutes the most widespread and to date, the most important coal-bearing horizon known in the Bowen Basin. Among the most important coalfields within these measures are the deposits of Theodore, Kianga, Moura, Baralaba, Bluff and Bluff North, Blackwater, Sirius Creek and Kemmis Creek...

The Blackwater Group is divided threefold into the Fairhill Formation, Burngrove Formation and Rangal Coal Measures on the western side of the Basin. Their equivalents on the eastern side are the Gyranda Formation, Kaloola Member and Baralaba Coal Measures..."

(Hawthorne, 1965: page 650)..."This formation" (Baralaba Coal Measures) "is known best in the Baralaba area... The upper part of the coal measures, as drilled, consists mainly of feldspathic calcareous sandstone with minor shale and siltstone, and contains the best seams of coal in the formation. The lower part is more silty and shaly with less sandstone and the coal seams in this part of the formation are either banded, or higher in inherent ash than the higher seams....seams are variable and splitting is common towards the south."

(Hill and Denmead (Eds.), Geological Society of Australia Journal, Volume 7, 1960, The Geology of Queensland: page 251) "Triassic sedimentation in Queensland was entirely terrestrial, no marine deposits having been recognized anywhere... The best known basin of deposition was that in which the Ipswich Coal Measures were laid down..., these deposits spreading continuously east and south from Ipswich to Brisbane... and south Moreton,... and north from Ipswich into the Upper Brisbane

Valley and Headwaters of the Burnett and Mary Rivers...

Sediments were deposited in the Ipswich Basin from the Middle Triassic to the Lower Jurassic. The Triassic succession consists of the Ipswich Coal Measures followed unconformably by the Bundamba Group...

The Ipswich Coal Measures consist of... freshwater shale and sandstone, some coal-bearing, together with conglomerate, breccia, tuff, and basalt (Denmead, 1955). The beds are characteristically lenticular...

The group is divided into the following formations defined by Allen in Allen and Staines (1959).

Blackstone Formation

Cooneana Formation

Tivoli Formation

Kholo Sub-Group."

(page 254)..."The Tivoli Formation comprises...sandstone, shale and sandy shale. The lower 550 feet are principally shale and carbonaceous shale with several coal seams... Alternating thick lenticular beds of shale and sandstone occupy the remaining 1,050 feet... The shale within the latter contain the productive seams of the North Ipswich mining district...".

(page 255)..."The Tivoli Formation is overlain conformably by the Cooneana Formation, a succession of massive medium-grained to coarse pebbly sandstones with thick interbedded lenses of shale. A few coal seams, noted for their lenticularity, occur in the shales...

This" (The Blackstone Formation) "formation, the uppermost unit of the Ipswich Coal Measures, consists essentially of shale, sandy shale and lenticular beds of sandstone. The shales generally contain coal seams: workable coal grades into non-carbonaceous grey shale both laterally and vertically. Practically all of the productive seams of the Bundamba mining district lie within the Blackstone Formation..."

(Anon: Queensland Government Mining Journal, 1949, Fig. A.11 is reproduced from this volume)..."The Callide coal measures" (Fig. A.11) "of Triassic age rest unconformably on Palaeozoic rocks and consist essentially of a basal section, predominantly conglomeratic, overlain by a thickness of... fine- to coarse-grained sandstones and subordinate shales, towards the base of which occurs the Callide seam. Both above and below the Callide seam minor coal horizons occur, but in these the seams would appear to be lenticular and therefore have no general significance from the economic viewpoint."

David, T.W.E., 1888: Progress Report for 1887: A Rep. Dep. Mines N.S.W., (1887), pp 142-152.

TABLE A.1

Permian-Triassic sequence in the Sydney Basin

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Reproduced from the Journal of the Geological Society of Australia, Vol. 16, Part 1, 1969.

TABLE A.2

Stratigraphic nomenclature and correlation of the Permian rocks of the Hunter Valley

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Reproduced from the Journal of the Geological Society of Australia, Vol. 16, Part 1, 1969.

TABLE A.3.

Stratigraphic units of the Illawarra Coal Measures in the Southern Coalfield

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* These units are individually recognisable in the northeastern part of the field (type area: Stanwell Park-Coledale), but are not always identifiable elsewhere.

** Includes 25 ft (7.6 m) of sandstone at this locality.

Reproduced from the Journal of the Geological Society of ~~Australia~~, Vol. 16, Part 1, 1969.

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General geological map of the Sydney Basin and the Northwestern Coalfield.

Fig. A.1

Please see print copy for image

Geological map of Hunter Valley.

Fig. A.2

Please see print copy for image

Stratigraphic column of the Greta Coal Measures at South Maitland.

Fig. A.3

Please see print copy for image

Stratigraphic column of the Greta Coal
Measures at Savoy Trig. Station.

Fig. A.4

Please see print copy for image

Stratigraphic column of the Tomago Coal Measures.

Fig. A.5

Please see print copy for image

Stratigraphic column of the Newcastle Coal Measures.
Note. Recently proposed (1969) nomenclatural changes are as follows: Cardiff Sub-Group *to* Adamstown Sub-Group; Highfields Formation *to* Glebe Formation; Wave Hill Tuff Member *to* Hillsborough Tuff Member; and Violet Town Conglomerate *to* Tingira Conglomerate Member.

Fig. A.6

Please see print copy for image

Stratigraphic column of the Singleton Coal Measures.

Fig. A.7

Please see print copy for image

Stratigraphic column of the Illawarra Coal Measures in the Southern Coalfield.

Fig. A.8

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Fig. A.9

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Stratigraphic Column,

Fig. A.10

Please see print copy for image

Fig. A.11